The Journal of

THE ROYAL AUTICAL IETY

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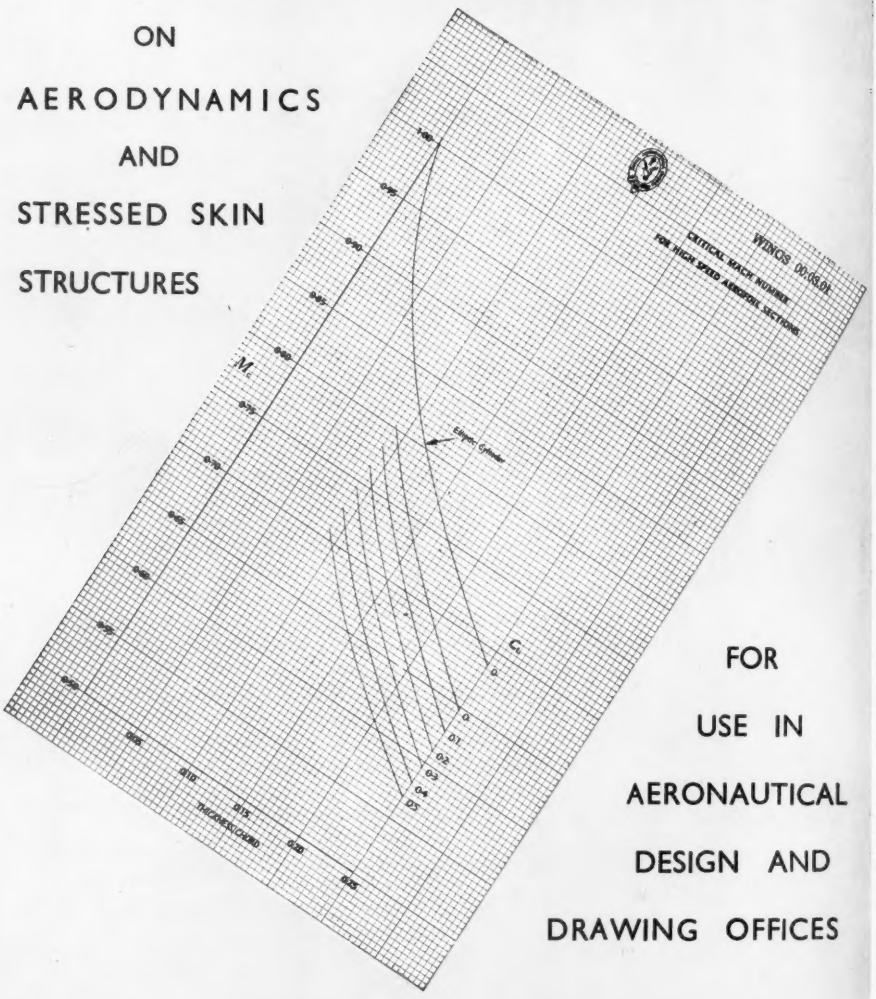

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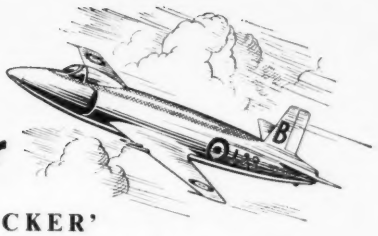

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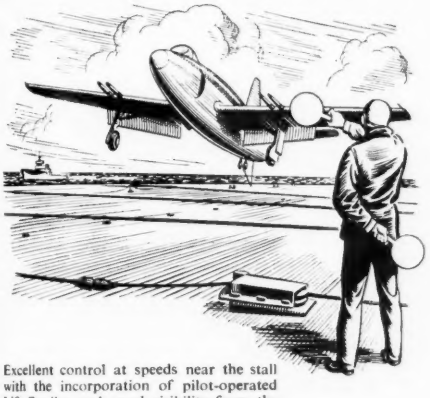

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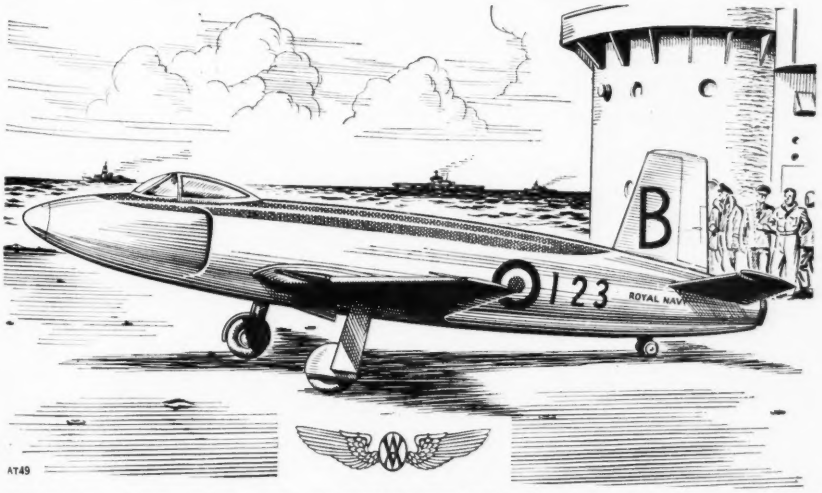

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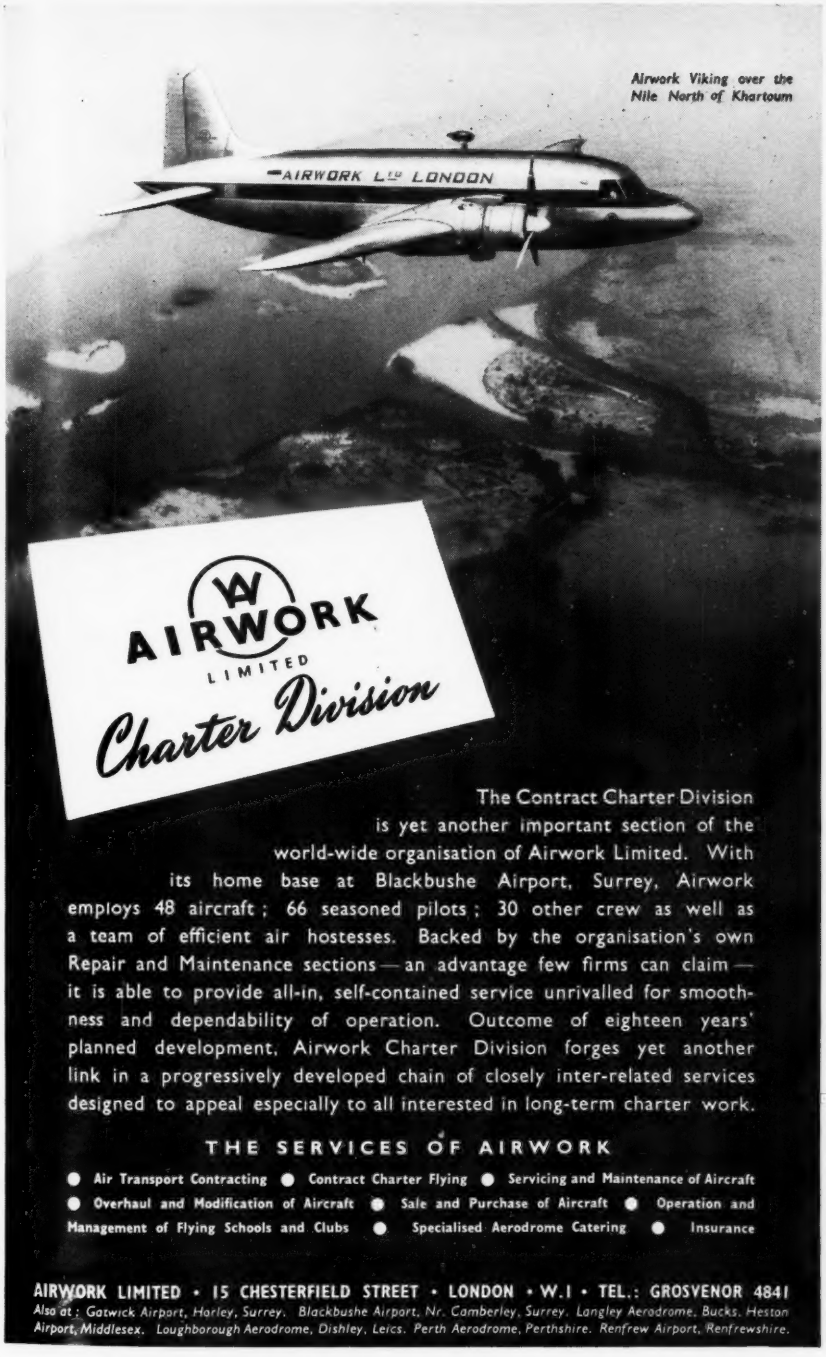

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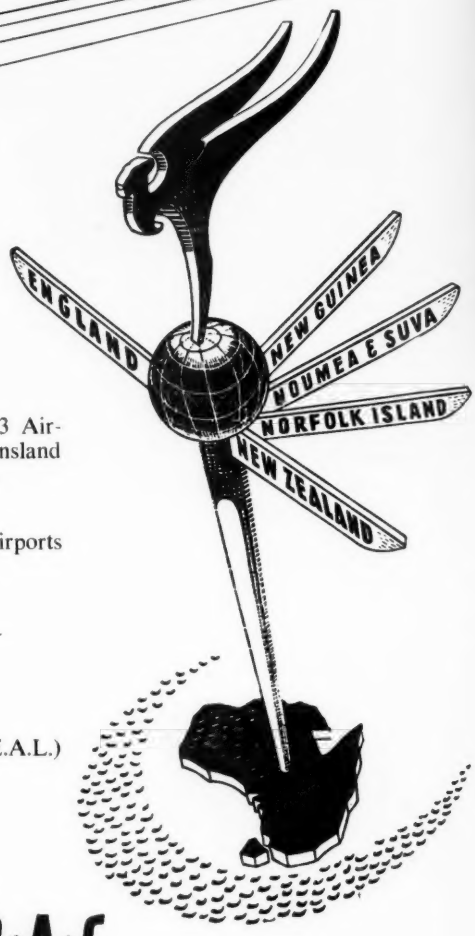

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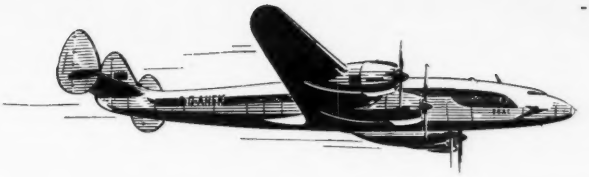

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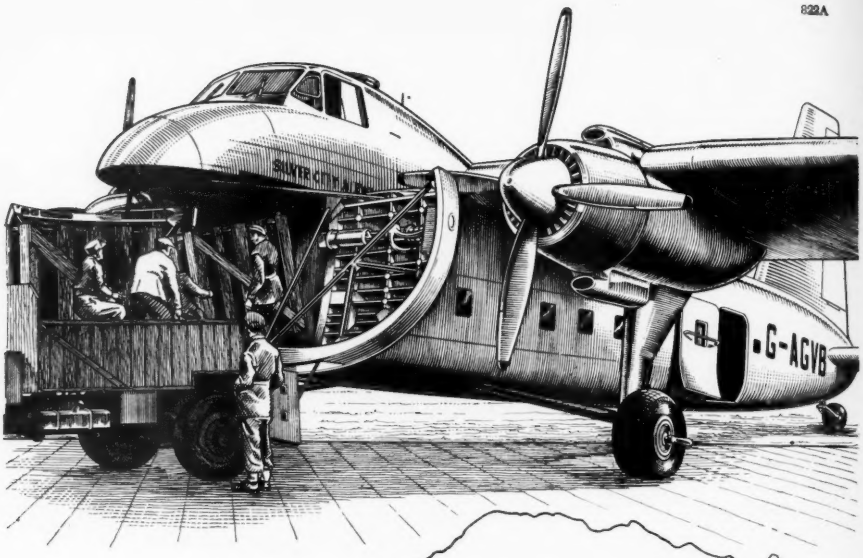

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8.12.48	Wunsdorf	Gatow	10,000	Grader.
	Gatow	Wunsdorf	10,000	Mail.
9.12.48	Wunsdorf	Gatow	10,000	Grader.
	Gatow	Hamburg	9,700	Machinery.
	Hamburg	Gatow	10,000	Red Cross Supp.
	Gatow	Hamburg	8,000	Misc.
	Hamburg	Gatow	10,000	Mixed Goods.
	Gatow	Hamburg	9,000	Machinery.
	Hamburg	Gatow	10,000	Food.
	Gatow	Hamburg	9,700	Machinery.
11.12.48	Hamburg	Gatow	10,000	Misc.
	Gatow	Hamburg	9,500	Machinery.
	Hamburg	Gatow	10,000	Newsprint.
	Gatow	Hamburg	9,500	Machinery.
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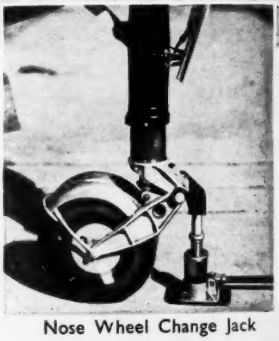

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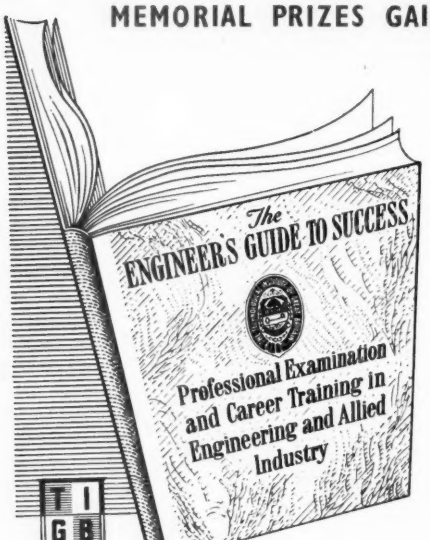

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Conferred for work of an outstanding or fundamental nature in aeronautics.

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Awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal
Awarded for the best paper read in any year before the Society on any science allied to aeronautics, *e.g.*, meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal
Awarded for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal
Awarded to the designer of any invention or apparatus tending towards safety in flying; open to members or non-members.

Society's Silver Medal
Awarded for some advance in aeronautical design.

British Silver Medal for Aeronautics
Awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal
Awarded under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

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The Wilbur Wright Memorial Lecture is held annually, a premium of £75 being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year.

British Commonwealth and Empire Lecture
The British Commonwealth and Empire Lecture is delivered annually by a lecturer chosen in alternate years from the British Dominions and Colonies and Great Britain.
The British Commonwealth and Empire Lecture has a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance will be paid towards the Lecturer's expenses.

R.38 Memorial Prize
Offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures
Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero-Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize
Offered annually for the best paper received by the Society on some subect of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize
Offered annually for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

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Offered annually for the best paper by a Student on some subject in connection with Aero-Engines. Its value is five pounds.

Major Baden-Powell Memorial Prize
Awarded in May and December of each year to the Student who is considered the best student by the examiners in the Society's Associate Fellowship examinations. Its value is three guineas.

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Awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is two and a half guineas for each award.

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Awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately five pounds.

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The Council offers an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

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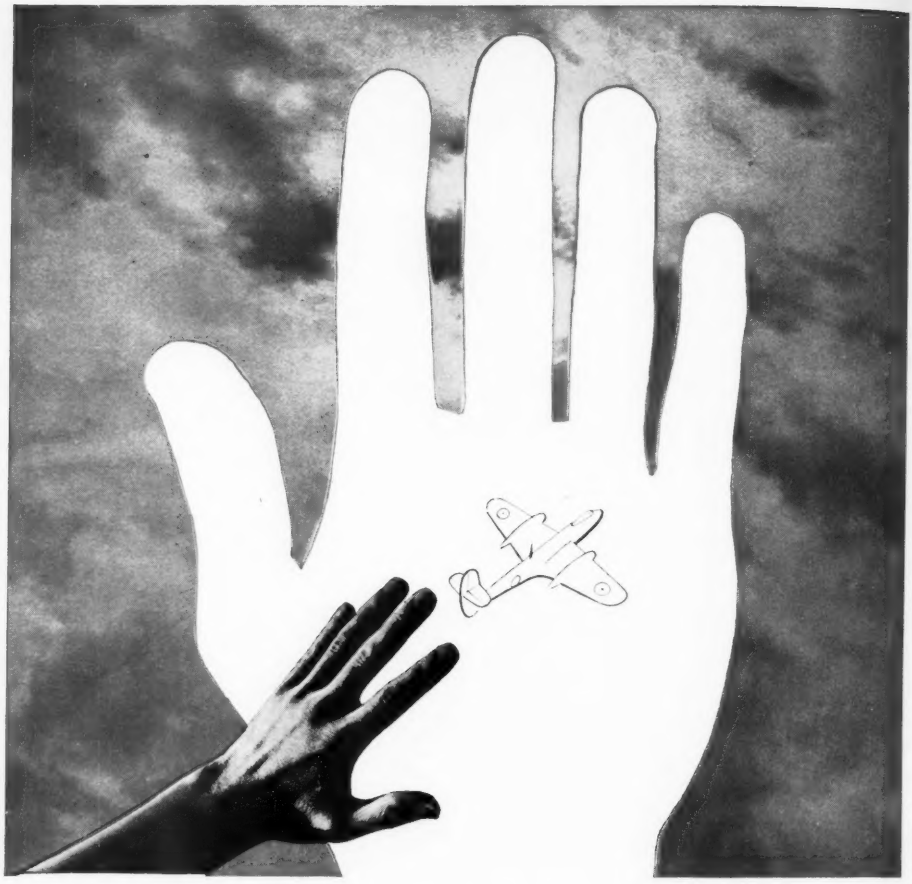

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HELICOPTER DISCUSSION

A JOINT MEETING of the Royal Aeronautical Society and the Helicopter Association of Great Britain was held at the Institution of Civil Engineers, Great George Street, London, S.W.1, on 20th November 1948, at which five papers on Helicopters were presented. They were the 756th, 757th, 758th, 759th and 760th papers to be read before the Society.

Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S., F.I.Ae.S., President of the Royal Aeronautical Society, presided during the first session. Opening the meeting Dr. Roxbee Cox said that although there were years of research and development ahead, the helicopter had arrived. In the Society the helicopter had been one of the matters to which long attention had been given, and it had obtained such importance that the Helicopter Association of Great Britain had come into being in 1945. Many of its members were also members of the Royal Aeronautical Society.

The first paper would be read by Wing Commander R. A. C. Brie who was the holder of Helicopter Aviation Certificate No. 1, an Associate Fellow of the Royal Aeronautical Society, a Founder member of the Helicopter Association of Great Britain and a Charter Member of the American Helicopter Society. Since 1947 he had been in charge of the Helicopter Unit of the British European Airways Corporation.

The second paper would be read by Captain R. N. Liptrot who had for a long time been engaged in performance work in the Air Ministry, the Ministry of Aircraft Production and the Ministry of Supply. At present he was Deputy-Director, Research and Development (Helicopters) at the Ministry of Supply.

Morning Session:

GENERAL PROBLEMS OF THE HELICOPTER FOR CIVIL USE

The Operational Point of View

by

Wing Commander R. A. C. BRIE, A.F.R.Ae.S., A.F.I.Ae.S.

INTRODUCTION

ALTHOUGH barely two years have elapsed since the helicopter was first certificated for civil use, the problems associated with its operation are sufficiently well defined to enable their nature to be discussed with reasonable facility. There are twenty-six years, including many tens of thousands of flying hours, behind this particular development and it is quite logical therefore that the most advanced and successful type of helicopter to date embodies the basic and well-proven rotor features of the Cierva Autogiro.

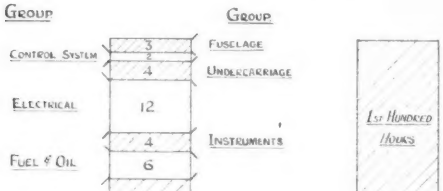
There is still much to learn and at this stage of development it has in many ways been advantageous that, so far, the field of operational use has been a professional one.

Difficulties have been minor rather than of a major category, but circumstances could easily have been otherwise had there not been constantly available the requisite background of skill and experience not only to cure, but what is of equal importance, to anticipate and prevent, trouble before it could assume proportions of a serious nature. Additionally, the limited number of helicopters in use has encouraged and made possible a rather intimate and desirable liaison between constructor and operator, which in turn has given the aircraft a reasonable opportunity to establish itself and prove its value under strictly controlled conditions of inspection and operation.

Essentially a product of the mechanical engineer, the helicopter with its clutch, gear boxes, driving shafts, universal joints, together with numerous ball, roller and needle bearings, is a mechanism comparable in many ways to that associated with more normal and accepted means of surface transport.

To enable the subject to be viewed in a proper perspective it is opportune and appropriate to draw attention to current achievement in Great Britain. Over a recent period of nine months covering more than 1,000 hours of experimental and day-to-day scheduled operation, there was on no occasion a cancellation or interruption of a flight caused by the failure of a purely helicopter component.

Whatever difficulties have arisen can be attributed to, and arise directly from, a lack of refinement in detail design.



Ratio of defects in various helicopter groups over 300 hrs. flying.

Incidence of overall defects over 300 hrs. flying.

Fig. 1.

GENERAL PROBLEMS

The general problems which I shall indicate and discuss fall under the headings of:—

Engineering
Flight characteristics
Operation.

Engineering

The application of continuous power to the main rotor, the need for uninterrupted rotation of this component in the event of power failure, and the provision of adequate means for torque compensation, involves mechanical complexity and multiplicity of moving parts. Moreover, the natural vibrational characteristics of the rotor system are such as to make the aircraft as a whole particularly susceptible, in terms of frequency and amplitude, to quite small departures from allowable tolerances on linkages.

The working life of main rotor blade hinge bearings, for example, is currently of too limited a nature. Compactness has been achieved at the expense of reliability, comfort and performance. Utilisation is impaired, inspection schedules are prolonged, and costs of operation appreciably increased, not only through enforced servicing, but also by the interruption in the working life of other components which would best function if left alone.

Ideally all components should have a stated life, their ready replacement and precise interchangeability being of primary importance. Even so, the possible reduction in maintenance man-hours thus effected is of itself inadequate unless the design layout of the aircraft has been such as to allow a concentrated effort to be applied, thus reducing turn-round time to a minimum.

Accessibility for inspection and replacement of working parts also necessitates easily removable panels, jacking and sling points, hand-grips and foot-rests. Dismantling and assembly of unitary components can only be accomplished with facility and little risk of damage by the provision of carefully designed tools and extractors.

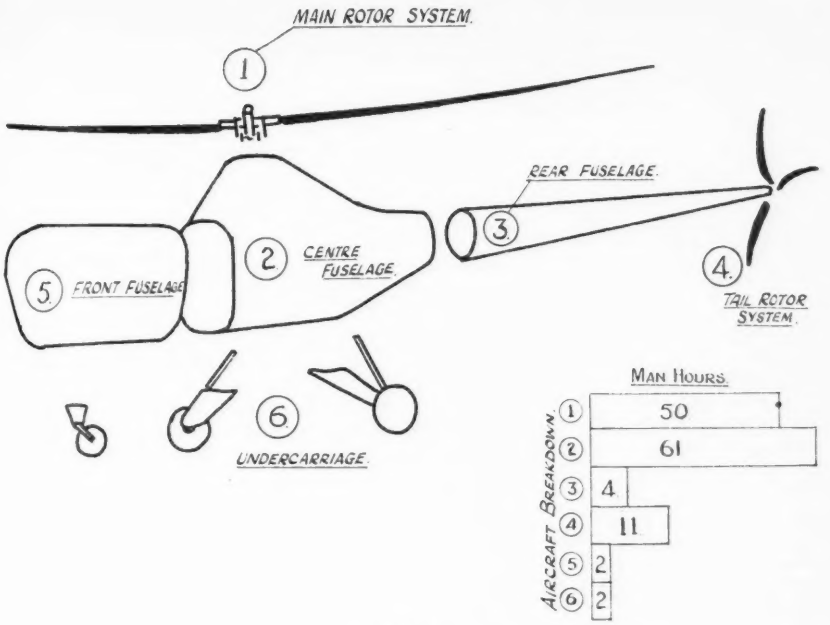


Fig. 2.
Component/man-hour breakdown for helicopter major inspection.

The suppression of friction involves adequate lubrication, particularly with highly loaded bearing surfaces. If a grease gun has to be used, correct positioning of the connectors is a minor point with major implications, second only to the selection of the correct grade of lubricant.

Thus, sound engineering practice during the initial design period is a vital factor in the determination of maintenance procedures and their relationship to, and influence on, utilisation. It is, in fact, the hard core of reliability, operability and earning ability.

Flight characteristics

Although the view is occasionally expressed that the helicopter is not difficult to fly, it would be an exaggeration to suggest that it is easy.

The efficiency of the control system as a whole is to a certain extent offset by delicacy required in the co-ordination of individual controls; lack of uniformity in sensitiveness and feel, and the inability to trim for any sustained period. Present unstable characteristics are thus accentuated and result in mental and physical fatigue for the pilot.

Although ballasting can be accepted as a pre-flight requirement to compensate for calculated C.G. displacement caused by the load carried, the lack of a satisfactory trimming device for use during flight necessitates the employment of the azimuth control, thus tending to restrict adequate control response to gusts, and adding to the difficulties associated with night and blind flying.

Careful investigation is needed into the positioning of controls and their relationship to normal movements of the body: cockpit comfort in terms of seating, visibility and temperature: and instrument display in terms of selection, grouping and readability.

The psychological aspect of helicopter pilotage, and its co-related influence on instinctive reactions — especially during abnormal conditions of flight—needs to be explored, for the mental capacity to think may not always be in step with the physical necessity to act.

Operation from confined, obstructed areas is appreciably influenced by performance

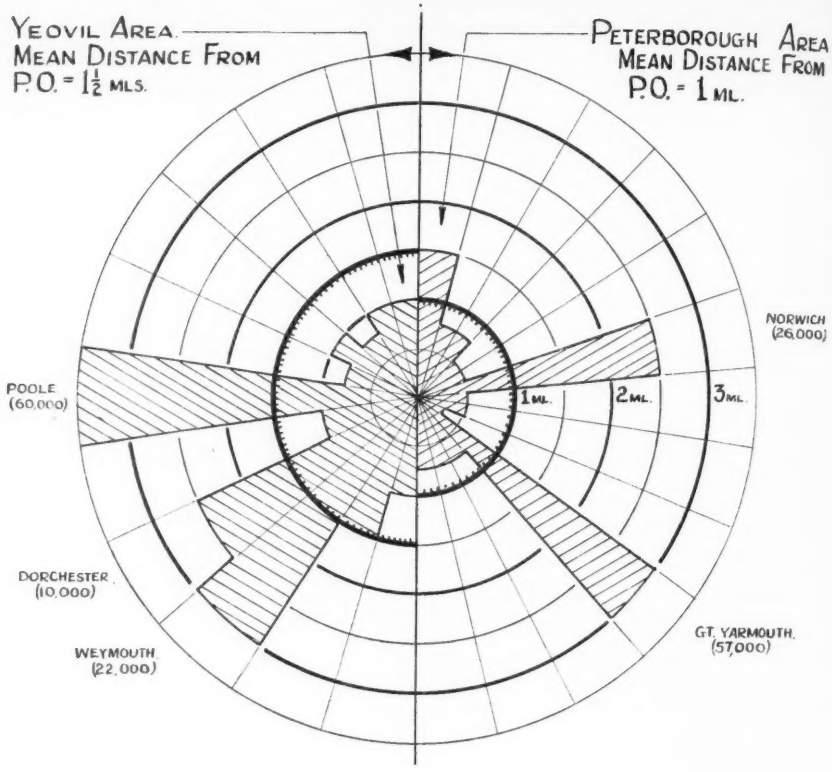


Fig. 3.
Distances from post offices to helicopter sites in Yeovil and Peterborough areas.

characteristics. Maximum safety necessitates a rapid rate of climb at a steep angle of ascent during the take-off. Conversely, and to facilitate landing in the event of power failure, particularly with single engine types, the rate of descent must be slow at low translational speed.

These latter requirements are functions of power and disc loading respectively, the desirable values of which should not exceed 10 lb. per h.p. and 2 lb. per ft.^{2} respectively.

Operation

Two essential operational requirements are that the equipment used shall be reliable and safe.

Maximum utilisation with minimum maintenance not only makes possible a high ratio of hours spent in the air to those spent on the ground, but this characteristic also breeds confidence among the operating crews in the reliability of the product they are handling.

Safety on the ground, both to crews and nearby spectators, must be assured by sufficient elevation of the blade tips of main and torque-compensating rotors.

For safety in flight, visibility from the pilot's seat must not be impaired by the external effect of rain, or internal misting. Preservation of accepted standards of transparency is particularly desirable during night and blind flying operations at low altitude.

For the carriage of passengers the fuselage must be roomy and easy of access; seating must be comfortable with a good view externally; and vibrational and sound levels must be of a low order.

Route selection, to a large extent, will be governed by either the lack, or limitation, of

normal surface facilities, three obvious examples being the centres of densely populated areas, mountainous terrain and water crossings. Hence, to preclude the possibility of a forced landing caused by power failure under these operating conditions, a twin-engined installation is obligatory; an essential performance requirement being the maintenance of altitude in the event of partial power failure.

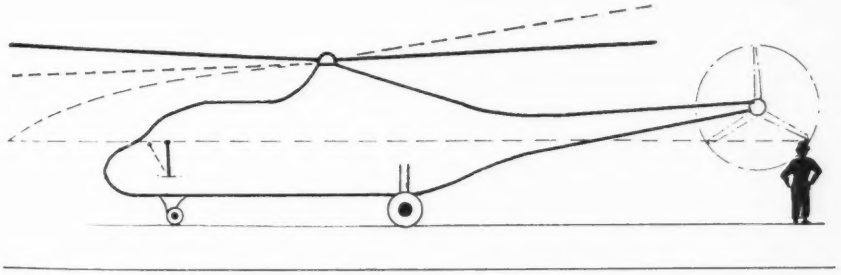
Closely associated and parallel requirements to which brief reference should be made, are the development of instrumental and navigational aids. Only by the ability to fly blind and at night will maximum utilisation and operationally acceptable standards of efficiency and economy be attained. The accurate identification and use of small landing areas also involves the development of suitable ground lighting equipment, the precise nature of which has yet to be determined.

The economics of helicopter operation are at present such as to preclude consideration of other than highly specialised uses, a limitation which arises from high initial cost, and low payload capacity. Thus the field of application will be restricted until the one bears a closer relationship to the other.

Although there may possibly be simple ways of increasing payload appreciably for freight or mail purposes, the solution so far as the human anatomy is concerned, appears to lie in the development of bigger and better helicopters. Here the economic picture tends to assume a more pleasing appearance, for a preliminary study based on current practice indicates the possibility of effecting an appreciable reduction in costs per passenger mile, and to a level more in line with accepted standards, with a 12—14-seater type of helicopter.

CONCLUSION

In endeavouring to cover a fairly wide field in the short time available, the object has been to indicate that although the helicopter has already arrived in a practical form, its further development is closely associated with a solution being found to many relatively small, but nevertheless important, problems. The subject of economics is a wide one embracing many variables, but there is little doubt that if there is to be any future in helicopter operation, if, in fact, the unique characteristics of this new means of transport with its



— HELICOPTER DANGER ZONES —

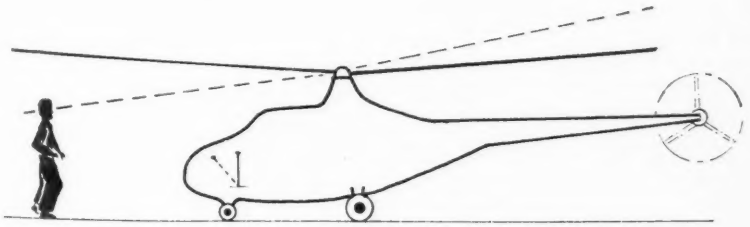


Fig. 4.

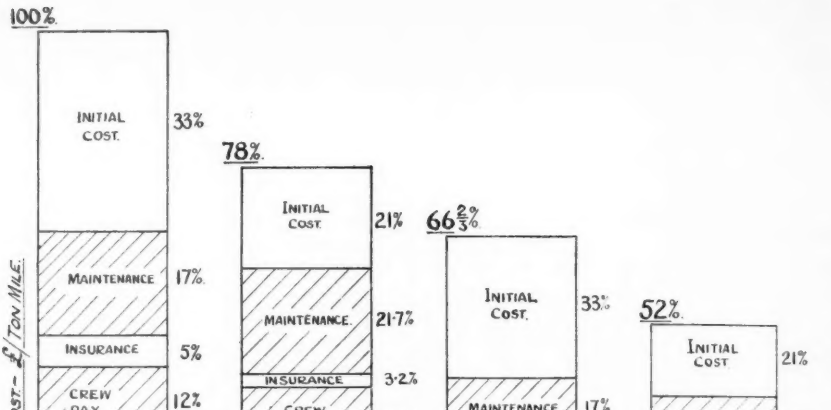


Fig. 5.
Factors affecting direct flight cost, 5,000 lb. helicopter, 1,000 hr. utilisation.

independence of specially prepared landing grounds and its ability to save time, are to be exploited to the full, then a fundamental requirement is that the Industry should produce an acceptable product at an acceptable price.

To ensure overall reliability in service, the term engineering must be considered in its broadest sense during the conception of any commercial helicopter, so much so in fact that if necessary it would be well worth while to sacrifice performance, in terms of high speed, on the altar of utilisation. Although man-hours expended on maintenance have an important influence on engineering costs, hours of unserviceability reflect adversely on earning capacity.

In summing up, the stage of development already reached in the rotary-wing art indicates clearly the need for boldness and enterprise in making the best use of knowledge which already exists, rather than in scanning fresh horizons with their inevitable uncertainties. There is nothing mysterious about what enables a helicopter to function, nor need there be any doubt about the direction in which its logical development should be pursued. If the Industry wishes seriously and profitably to participate in this comparatively virgin field of vast potentialities, it must keep its head clear of the clouds of theoretical procrastination and place its feet firmly on the ground of practical reality. This does not imply that improvement is not desirable, but it does imply the necessity for a sharp dividing line to be drawn between long-term research, and short-term development.

The latter is our immediate concern and satisfactory solutions to the operational problems involved will only be reached expeditiously by mutual co-operation between those who produce and those who operate.

The Technical Problems of the Civil Helicopter

by

Captain R. N. LIPTROT, C.B.E., B.A.

INTRODUCTION

WHEN we examine the helicopter problem critically and the characteristics of available types, the special problems which stand out for investigation during the next stage of development are as follows.

1. VIBRATION

The least informed on the subject will immediately realise that when the rotating lifting system of a helicopter is in translation, the velocities and, therefore, the lift on the blades on the advancing and retreating sides are very different, so that in the absence of some special arrangement there would be an upsetting couple about the longitudinal axis. This can only be corrected by a periodic change of the lift and drag forces on the blades, so we can expect to experience severe vibration.

The classic solution is the flapping blade introduced by Don Juan de la Cierva, which not only balances out the dissymmetry of lift, but relieves the blade roots of the periodic bending moments. This solution was elegant, but, unfortunately, instead of relieving the vibration problem, it actually accentuated it. This arises in several ways:—

(*a*) The longitudinal flapping caused by the forward motion results in a tilt of the tip path plane with respect to the axis of rotation and, in addition, the tip path plane has to be tilted by some form of periodic control in order to trim the aircraft at the attitude necessary for the speed. There is, therefore, a dissymmetry in the plane at right angles to the axis of rotation and periodic forces in that plane.

(*b*) In addition, a flapping blade is subject to a Coriolis acceleration in the plane of rotation. Perhaps the simplest way of explaining this is to point out that, as a blade flaps upwards, the distance of the centre of mass from the axis of rotation decreases. For constant r.p.m., however, the product of this distance times the angular velocity must remain constant, so that the blade in effect must accelerate as it flaps upwards and decelerate as it flaps downwards. This again involves periodic forces in the plane of rotation.

These two dissymmetries make it necessary to introduce a drag hinge, in order to relieve the blade root from the periodic bending moments which otherwise would tend to cause blade fatigue failure. The introduction of the drag hinge leads us into further trouble, since the natural frequency of one of the modes of oscillation of the blade about the drag hinge is close to that of the periodic forces, so that we get an unstable hunting oscillation, unless the freedom of movement of the blade about the drag hinge is restricted by damping or the natural frequency is raised by some means.

(*c*) As the ratio of forward speed to rotational speed increases, the retreating blade is more and more stalled and for this reason again vibration is experienced.

(*d*) In the helicopter, where forward motion is obtained by tilting the tip path plane, there is an added axial flow through the disc, which reduces the effective angle of attack of the blades. The tip sections are affected less than the root sections, so that as the collective pitch is increased to maintain the average lift at the required value, the tip sections are overpitched and periodic stalling occurs.

Enough has been said to show that in forward flight we have a veritable witch's cauldron of fluctuating forces and a vibration problem which, although it may delight the heart of a vibration engineer, is one of the main headaches for the poor designer. Vibration indeed, rather than compressibility effects, may be the major factor in limiting the top speed of helicopters.

I want to introduce a word of warning. Some designers have considered that it is sufficient if the vibration is isolated from the aircraft. Even though isolated and, therefore, not impinging on one's senses, the periodic forces are still there and will promote fatigue failure.

2. SIMPLIFICATION OF CONTROL

There is widespread belief that the helicopter is difficult to fly, and we have all heard of pilots with thousands of hours on fixed-wing aircraft who, in the early days of their conversion to the helicopter, have despaired of ever getting the hang of the thing. It is perfectly true that existing helicopters prove to be extremely difficult to master for some pilots. It is probably true to say that it is far easier to train an *ab initio* pupil, who has never been in the air before, than an experienced fixed-wing pilot.

This, in part, is because of a psychological effect, in that the skilled pilot at first cannot bring himself to break all the rules of the game on which his very life depends on a conventional aircraft; for example, in flying at maximum speed and deliberately coming to a standstill when some 20 ft. above the ground.

In the fixed-wing aircraft, although it has the six degrees of freedom of any body in space, we can get complete control from three angular controls and the throttle, since the aircraft can only move, at least continuously, in the direction in which its nose is pointed. The helicopter, however, as our American friends put it, can move in 362 directions, *i.e.*, along any azimuth as well as up and down along its axis. At least one additional control, therefore, is required—the collective pitch control. As the human being only has two hands and two feet, two of these controls, the throttle and the collective pitch, have commonly been operated by one hand, and it has been the correct co-ordination of these two which has complicated the issue for the pilot. On top of this, in what has become the classic configuration, *i.e.*, the single main rotor with tail rotor for torque compensation, there is a further difficulty that any use of one control demands co-ordinated adjustment of other controls; for example, use of the tail rotor as a yawing control absorbs more power when turning against the torque reaction than with it, so that an appropriate throttle adjustment has to be made if height is to be maintained. Conversely, any adjustment to the throttle or collective pitch alters the torque reaction and so involves the use of yawing control. In sideways flight opposite rudder must be applied to keep the aircraft heading correctly, and this again involves throttle and/or pitch correction to maintain height.

Again, there is a lag in response to azimuth control, although the control is extremely powerful and requires only very small application and the response is normally far quicker in the rolling sense than in the pitching sense, because of the big differences in inertia about the two axes. For this reason, the pilot tends to over-correct and to start violent swings which can result in an accident when flying close to the ground.

I would stress that it is only in the early stages that there is any real difficulty in control. Once the pilot gets the hang of the thing he can relax a little and flying becomes relatively simple. Nevertheless, flying helicopters demands a good deal of concentration and in the next generation of helicopters the controls must be simplified and some of the co-ordination of the controls must be done for the pilot by some mechanical device, in order to relieve the fatigue which to-day is quite severe.

3. STABILITY

Mr. Stewart in his lecture* gave a very full account of this problem, so that I need not go into detail. It will suffice if I say that, with the increasing use of the helicopter for commercial operation, we must be able to cater more and more for adverse weather. This is especially important for any of those uses where a rigid time schedule is demanded, as, for example, for postal services. Intrinsically, the helicopter is the safest of all flying machines under low visibility conditions, since it can adjust its speed to be appropriate to the visibility at the time. Under blind conditions, however, where the pilot has to give his whole attention to navigation, radio, contacts with controls and so on, stability characteristics which might be acceptable under contact conditions even in low visibility become quite untenable. Moreover, we can expect increasing use of the helicopter by private owners and others who cannot be given an aircraft with undesirable handling qualities, even though such poor qualities

* STEWART, W. The Flight Testing of Helicopters, JOURNAL of the R.Ae.S., May 1948.

might be overlooked, to some extent, by skilled operators or for purely military use.

It is important, therefore, that the designers should give us improved stability, certainly under normal cruising conditions and preferably under any conditions of flight, including hovering.

4. SAFETY

The helicopter, in common with the Autogiro, is the safest of all aircraft, since it cannot be stalled in the ordinary sense of that term. Even though its speed is inadvertently reduced right down to zero, it will sink on a level keel under full control. In the event of power failure, it is converted to auto-rotation by pitch reduction and it can then make a safe forced landing in a small clear space, exactly like the Autogiro. I realise that in making such a sweeping statement as this I am likely to be criticised, but I make the statement deliberately in order to stimulate discussion and get the answers from the designers.

There is the difference in the helicopter that, in order to ensure the maintenance of r.p.m., the blade pitch must be reduced rapidly, otherwise, with the blade angles commonly necessary in ordinary flight, the rotor would slow up below the safety line in a few seconds. It is for this reason, coupled with the need to simplify the co-ordination of pitch and throttle, that some form of constant speed unit has been advocated, so that in the event of power unit failure the change to auto-rotation is immediate and automatic, and does not require any emergency action on the part of the pilot.

A word of warning is perhaps necessary on constant speed devices. Most of the devices proposed so far, follow the lines of the constant speed propeller, *i.e.*, the governor operates direct on collective pitch. These devices are not satisfactory, since they introduce a hazard of their own in that, in the event of power unit failure close to the ground, they take the wrong remedial action, since, under these conditions, the collective pitch should be increased, so using the kinetic energy of the rotor to arrest the landing and, as the pilot himself has no control over collective pitch, he himself cannot take the right corrective action. On the other hand, if the governor operates on the throttle while co-ordination of pitch and throttle is done automatically for the pilot, the collective pitch lever becomes his master control and he still has to manually decrease pitch in the event of engine failure.

There is a further difficulty that, in the helicopter state, the air flow is through the disc from above downwards, whereas in the auto-rotative state it is upwards through the disc. Also, if the engine failure occurs at slow air speeds, it is necessary to pick up speed in order to obtain the minimum rate of descent on the glide. To pick up the necessary air speed from hovering and to establish the new flow pattern, the average loss of height is of the order of 300 ft., decreasing with increase in air speed at the time of the engine failure. This is the one real potential hazard with the helicopter, and to-day pilots are instructed not to fly at low speed between, say, 30 ft. and 300 ft.

If the single-engined helicopter is to be permitted to operate over built-up areas, it will be essential to remove this potential danger and, in any event, it will have to be catered for, since so many of the practical uses to which the helicopter can be put—for example, crop-spraying—demand flight at low speed, even hovering and at relatively low heights.

5. MAINTENANCE

I think that nobody with operating experience on the available helicopters will disagree with me when I say that it is not the admittedly high initial cost of the helicopter to-day which has taken the gilt off what looked like ginger-bread to the early helicopter operators; it is the maintenance costs because of the direct labour in short period inspection and overhaul, the excessive requirements of replacement parts, and the lost time caused by unserviceability, which have damped the ardour of the most enthusiastic. It is true that maintenance crews with their built-up experience have made great advances in more rapid maintenance and servicing technique, but the costs have stabilised at too high a level.

Frequent dismantling and inspection to preserve airworthiness and smooth operation were well worth while when we were gaining experience, but that time has now been passed and in far too many existing designs, when undertaking this work the maintenance crew is faced with an exceedingly complicated mechanism which is over-expensive to take down and inspect, if only because of the

number of parts involved. For example, in transmitting the cyclic pitch control from a swashplate to the blades, too many parts are used. A very small amount of wear at each joint causes an overall amount of backlash in the system, which involves early scrapping of many parts. This motion could far better have been transmitted by a single link, increasing the life between overhauls and cutting down expensive replacements.

Ball or roller bearings at heavily loaded flapping, drag and feathering hinges, are a source of continual trouble because of friction oxidation (the so-called " False Brinnelling ") which occurs in bearings where the angular movement is small. Friction oxidation causes very short bearing life as compared with a normal fatigue failure of the same bearing for single direction continuous motion, and it is only by reducing the load rating to about one-third of the unidirectional rotating rating that one can get a satisfactory life in the applications which we are now considering. This phenomenon, although known already in many industries, has not been realised generally by the helicopter designers, who have chosen their bearings on the makers' normal ratings and, as a result, bearing replacement has been one of the major causes of high maintenance costs. Similar early failure of universal joints at points where angular change in direction of shafting is only one or two degrees, was a fruitful cause of unserviceability and need for replacements in the early operational helicopters. Research on this phenomenon and the development of bearings which will give longer life under oscillating motion at small amplitude is urgently needed for the helicopter.

Most helicopters to-day are characterised by the complete inaccessibility of their power plants. Engines are enclosed in cooling air ducts, completely boxed in by fire-walls and close to fuel and oil tanks in such a way that they can hardly be seen, even by the most conscientious mechanic, and so receive little or no preventive maintenance. Cases are known where the fuel tanks have to be removed to enable the plugs to be cleaned. The designer all too often in the past has been responsible for an arrangement in which the aircraft virtually has to be dismantled in order to change the engine. Maintenance under such conditions is naturally difficult and the designer must do better in future.

Discussion

W. Tye (Air Registration Board, *Fellow*): On the general layout of rotor systems in present-day helicopters, Mr. Hafner would probably say why it was best to react the main rotor torque with a little fan stuck several feet behind where any decent fuselage ordinarily stopped; Dr. Bennett would then explain why the same function was so much better performed by a propeller asymmetrically mounted; and Mr. Shapiro might even try to convince the meeting that both these solutions were wrong, and that the real answer was to suspend the helicopter from three remote corners. Perhaps the problem was comparable with one debated many years ago on monoplanes, biplanes or triplanes, and whether the tail should be in front or behind. He did not know who was right or who was wrong about the helicopter, but insofar as any residual engineering instincts were left to him, these instincts rebelled against all these configurations. His instincts did not tell him what a helicopter should look like, but he hoped that someone might supply the answer.

The authors had referred already to a number of directions in which improvements could be achieved, both in efficiency and safety. These two developments must proceed hand in hand, although inevitably they would pull in opposite directions. The aim of airworthiness people was to see that a reasonable balance was maintained between the two.

The problem was by no means new, for it had to be faced every day with fixed-wing aircraft, but in that latter sphere they had many years of experience to guide them. In the helicopter field the experience was much shorter, and he felt it would be easy to allow safety to suffer in the interests of efficiency, or vice versa. The only satisfactory answer was to obtain as much information as quickly as possible about the way in which helicopters behaved in operations or simulated operations.

The following were examples of things they needed to know:—

The loads applied by the pilots in manœuvres; information to assist in the

determination of fatigue conditions for rotor blade design; the velocities of descent in normal and emergency landings; the use of engine power in typical flights; the effect, if any, of ice on the rotor blade; the degree of stability necessary for safety.

He had served on the Air Registration Board's Rotorcraft Requirements Co-ordination Committee, on which designers, engine constructors, operators, and specialists from the R.A.E. and the Ministry of Supply were striving to prepare a design code which would establish and maintain a reasonable level of safety. The Committee's task was made extremely difficult by the absence of the kind of information to which he had referred.

O. Fitzwilliams (Westland Aircraft Ltd.): He wondered if Mr. Tye objected to sailboats. He could think of nothing more asymmetrical than those time-honoured vehicles. From a performance standpoint it did not seem to matter in practice how many rotors there were or where they were placed. It was a matter of engineering convenience; they could not do what was required with just one rotor without some form of jet drive, and they had to choose the most economical means.

Surely one object of the meeting was to enable the helicopter fraternity not only to explain their problems but also the reasons for their obvious enthusiasm, in the hope that more of the highly qualified and experienced people in the aviation industry might be led to see in the helicopter a fascinating and thoroughly useful outlet for their talents. He could not help feeling that those with a wider experience of aircraft engineering along orthodox lines would have noticed that most of the complaints which had been made about the helicopter were of a curiously minor nature. The main hold-up in helicopter development was not because of the existence of mysterious problems which could be handled only by a genius; it was, and always had been, lack of funds and lack of volunteers from the ranks of the more talented and experienced aircraft engineers.

He thought that, far from being complicated, every successful rotor system now flying was of a simplicity approaching crudity and the contrary impression was an illusion arising from unfamiliarity with the simple swashplate mechanism involved. The reliability of the mechanism was astonishing, considering the small extent of the facilities which had been available. Improvement was a matter of skilled, but nevertheless straightforward, aircraft engineering. Surprising attention had been paid to the servicing aspect in the existing helicopters. It was not true to suggest that they were lacking in proper provision for maintenance. Also, their power plants were reasonably accessible. They were not perfect, and to suggest that maintenance was entirely satisfactory would be untrue, but in at least one type that was operating there had already been serious complaints that the time and energy called for on inspection schedules was out of all proportion to the trouble that was actually found in the machine when it was inspected. Some of the major parts, the tail gearbox and so forth, were not even dismantled for inspection over a period of something like 600 hours.

Insofar as difficulties of this sort did exist, they did not involve anything peculiar to the helicopter nor anything which could not be cured by straightforward application of money and man-power in the design offices. Without those progress must remain slow.

The same remarks in the same degree could be made about stability and most of the other problems discussed. In considering stability, they must think of the use to which helicopters were put and the kind of helicopter with which they were dealing. For passenger operations twin-engined helicopters were needed because passenger operation meant efficient service into and out of the principal towns.

At present helicopters were mostly single-engined and mainly used for specialised duties, such as crop spraying, rescue work.

In a recent lecture to the Helicopter Association Dr. Sissingh had described a most elementary collection of bars and links which could perform all the functions of an otherwise highly expensive automatic pilot. He did not think there was a designer in this country who would at the moment bother to incorporate it, for it was just not worth while in present conditions. Later on, when they needed stability in passenger operations, and a great deal of work had already been done on the stability of the multi-rotor arrangements, when the law of supply and demand called for it, stability would be provided.

Much the same could be said of cures for vibration. He believed Mr. Shapiro would point out that the vibration which bothered the occupant of the helicopter at the moment

was due mainly to lack of foresight and effort in the design offices, which was unavoidable at the moment. The vibration which was really inherent in the helicopter and which could not be eliminated, was small compared with the vibration of ordinary surface means of transport. If they wanted to fly helicopters at speeds much above 140 m.p.h., where vibration problems really became severe, they might have to use forward propulsive airscrews and possibly fixed wings, but such aircraft should probably be called "convertaplanes," rather than helicopters.

The further development of helicopters was dependent mainly on the money and manpower available, but the helicopter manufacturers were not waiting; they were going ahead with the production of helicopters, confident that customers would buy and use them and thus provide the funds necessary to bring the helicopter to the state of perfection desired by the operators.

L. S. Wigdortchik (Helicopter and Rotary Wings Ltd., *Assoc. Fellow*): He believed the future of the helicopter was dependent on its commercial potential to an extent that set it right apart from the fixed-wing aircraft. The latter, because of its over-riding military value, had never lacked funds for its development, but such an all-important incentive did not exist for the helicopter. Therefore, they must understand from the outset that it was essential to make the helicopter a commercial proposition with a realism, and even ruthlessness, not hitherto seen in aviation.

There was no longer any real problem in making a helicopter with acceptable flying characteristics; and, as the authors had shown, the practical problems were well on the way to solution. The real problem was to produce a helicopter that could be made a commercial success by an efficient operator.

Close economic analysis of contemporary helicopters showed that the operating costs were high and out of all proportion to the general service rendered, mainly because of the high ratio of initial cost to disposable ton-miles per hour. Commercially, they could only be considered in rôles where either the payload against distance carried had a high intrinsic value, or a special service or novelty aspect was exploited.

To some extent it might be possible to produce cheaper and more efficient machines by simplification of detail and overall design, without impairing ultimate performance and reliability. Was it really necessary to follow fixed-wing requirements for undercarriages, structures and other design criteria? Similarly, could requirements for vertical flight performance be relaxed, in order to be able to operate at heavier all-up weights? The engine-off landing was no longer such a hazard as they had thought. Again, many existing helicopters carried excess structural weight, because of the unknowns that existed during their design stage. To-morrow's helicopters would benefit by later experience.

He believed that a great advance in commercial characteristics would be obtained with the large helicopter, in the 1,500-3,000 h.p. class, since all indications showed that such machines would have a much lower ratio of initial cost to disposable ton-miles per hour. Such an aircraft would have to be able to maintain a ground speed of 100 m.p.h. against a headwind of 40 m.p.h. over blocks of 250 miles and must be able to carry 20-30 passengers.

It was no use having helicopters if they did not know how they were going to use them and over what routes. The work being done to-day was valuable in the operating lessons that were being learned, and from that they must take their guide. His own view had always been that the helicopter was best suited for passenger transport because of its ability to reach city centres, but it must be able to offer a service that soon became indispensable and that could only be done by a service with a utility far in excess of anything that went before.

The history of vehicles showed that they became really economic only when mankind evolved his society around their potential. The helicopter had a chance to become part of the human fabric to an extent which might confound their thoughts to-day.

Air Commodore W. H. Primrose (*Assoc. Fellow*): In his British Commonwealth and Empire Lecture* Mr. Masefield had laid down four basic requirements for air transport to achieve its rôle as an economic medium in the communications system:—

1. Efficient aircraft.
2. Efficient operators.
3. An efficient ground organisation (meaning adequate airports and adequate air traffic control).
4. An air faring outlook—by the public.

*MASEFIELD, P. G. Fourth British Commonwealth and Empire Lecture. Some Economic Factors in Civil Aviation. JOURNAL R.Ae.S. Oct. 1948.

The first and second of those requirements had been dealt with adequately in the first two papers, but there was a complete absence of any mention of requirements 3 and 4.

Let them assume that within the next five years intensive research and development would result in the production of the acceptable product at the acceptable price demanded by the operator, together with the evolution of a satisfactory operational technique and trained personnel. How far advanced would they be towards the practical economic utilisation of the helicopter as a means of speeding up communications if there were no developments in the provision of city centre landing sites and other ground facilities? Without those, few of the advantages which the special characteristics of the helicopter possessed over other forms of transport could be reaped. It would be like having efficient trains or buses without railway tracks, roads, stations or termini.

The fourth requirement and the one which Peter Masefield had considered most important, was an air faring outlook. Even the provision of "City Copter Courts," as they had been called, would not ensure the full economic utilisation of the helicopter transport potential, unless the public were educated to be helicopter-minded.

The aeroplane, because it had to run along the ground before it could become airborne, and on landing after it ceased to be airborne, *must* have some form of wheeled undercarriage. The helicopter, because of its ability to take off and land vertically without forward run, did not require the wheeled undercarriage. There seemed to be considerable room for the development of an alighting gear which would save a lot of weight and/or drag and at the same time would provide a good shock-absorbing medium. Such a landing gear could also be made to spread the load over a larger area and so make less stringent the bearing strength requirements of landing sites. If it were an air pressure type it might also provide the facility for the helicopter to alight on water and float in a stable condition. The advantages of such an amphibious type required no stressing.

A point in the economics of helicopter operation that was too often not fully appreciated, or was entirely overlooked, was that of its facility for rapid turn-round. That might well give it the advantage of at least 10 minutes at each end of a stage journey over the normal transport aeroplane. On a stage journey of 100 miles at 100 m.p.h. enough time would be saved for an extra journey every three hours or so, which would go a long way towards nullifying the higher translational speed of the aeroplane, apart from time saved in surface travel between city centre and airport. He thought that Mr. Masefield had not made full allowance for that factor in his comparison of the aeroplane and the helicopter on the short stages.

S. Scott Hall (P.D.T.D. (A) Ministry of Supply, *Fellow*): He appreciated that Mr. Fitzwilliam had promised that when they had helicopters with multi-rotors the problem of stability would be solved. But it was important to consider the helicopter as it was to-day, and he understood that it still lacked stability. He had tried to fly an early helicopter and it had seemed to him very much like trying to balance a ball on the end of a pin; it was certainly unstable.

There was also the difficulty of flying blind, and he hoped that these two points would be dealt with adequately in the discussion because he regarded them as being fundamental. Good stability and blind flying qualities were absolutely essential to operation in bad weather.

A. McClements (Helicopter Unit, British European Airways): If they came down to fundamentals, economics would probably play a much bigger part than anything else in determining when helicopters would become available as a means of transport to the "man in the street." One of the factors affecting economics was closely related to helicopter engineering and maintenance procedures, and much could be done by the designer and operator which would reflect favourably on the overall economic picture.

Maintenance methods at present slavishly followed the tradition of past aeronautical practice. They inspected machines at given periods, pulled them to pieces at other periods and put them together again, often doing more harm than good in the process. More important they kept the machines on the ground during those performances. Some idea of the drain which such methods imposed on the operator could be gathered from his own experience, which showed that for every hour flown by a helicopter they kept it standing on the ground tinkering with it for approximately $2\frac{1}{4}$ hours. That figure bore no relation whatsoever to the reliability of the type of machine in question. In actual

fact, current certificated helicopters were known to be remarkably trouble-free.

Such methods gave some assurance against breakdown and accident, but they were so unattractive economically as to make it obvious that attention must be paid in future designs to ensure higher utilisation and less maintenance effort. They would go a long way towards their goal, and at the same time probably make one of the most forward steps in helicopter development for some time to come, if they worked on the following lines:

(*a*) A realistic balance must be struck between performance and possible useability. The designer must try to give the operator the maximum possible utilisation potential for the minimum amount of engineering maintenance effort. The future commercial helicopter which would be popular would not necessarily be the one which had the highest performance, it was more likely to be the one which was reliable and required little attention.

(*b*) The present system of maintenance in which all effort was aimed at discovering defects by searching for them at frequent intervals should be abandoned. The manufacturer should find out what the lives of his helicopter components were, and let the operator leave those components alone until their lives were over and then change them. This implied considerable effort by the manufacturer in the initial stages of a project, embracing bench and laboratory testing and full-scale evaluation under conditions of controlled intensive flying. Such effort should be undertaken before the machine was offered for regular operation.

(*c*) The closest attention should be paid to interchangeability and accessibility so that parts could be replaced quickly and without the need for "fitting."

(*d*) The closest attention should be paid to easing the problems of servicing.

(*e*) Adequate special tools should be provided so that servicing and maintenance could be done easily and quickly.

There was nothing particularly original about those suggestions. The lecturers had clearly touched on most of them and people interested in fixed-wing aeroplanes had been making similar suggestions for some time. There was one important difference between the commercial aeroplane and the commercial helicopter; the helicopter had no background of convention to overcome and they had a golden opportunity to start it off properly.

Group Captain E. Fennessy (Decca Navigator Co. Ltd.): The navigation of the helicopter was a very different problem indeed from that arising with the fixed-wing aircraft. Bearing in mind the vast size of modern airfields used by fixed-wing aircraft, it was not so much a problem of finding those airfields; indeed, they could hardly be missed. The major problem of fixed-wing aircraft was to get them down in safety. On the other hand, the helicopter had to land in a small space, which probably had to be approached by a devious route. The problem was more akin to that of marine navigation, where ships had to proceed by devious channels in close proximity to dangers in order to reach restricted and confined ports. But in a ship, it was possible to carry considerable amounts of navigational equipment, without regard to weight, and extensive facilities could be provided for plotting the ship's position and course on Charts. In the helicopter, navigational aids must be of minimum weight, and furthermore, since the pilot was fully occupied with the problem of flying the helicopter, no technique involving any procedure of plotting the position would be acceptable.

The pilot must have provided for him, in an automatic fashion, adequate information to enable him to follow the proper route in any weather and without his being involved in any manual operation, other than that required to switch the equipment on at the start of the flight.

It was encouraging to note that many of those concerned with helicopter operation appeared to be well aware of these operational requirements. As a radio engineer concerned with co-operating with the aeronautical engineers and the operating authorities, it was a pleasant experience to find such an awareness of the necessity for an early solution of these problems. There was, indeed, a more live realisation of the need to solve the problem than was perhaps existing in the field of fixed-wing aircraft navigation and control.

The Decca Navigator Company were working in close collaboration with the Helicopter Development Unit and the Research and Development Division of British European Airways, on the solution of those problems of automatic navigation.

The principles being followed were that firstly, a radio navigation system should be provided which gave the adequate basic information and the aircraft's position, and it had been found in trials conducted by British European Airways that the Decca System provided this basic facility. To interpret this information to the pilot in an automatic manner, the Track Control Unit had been developed. This was an electronic interpreter, in which the aircraft's position, derived from the Decca System, was converted to a simple meter display, telling the pilot his position with respect to track, in terms of both his distance to left or right of track, and his distance to fly along track to destination. The pilot had therefore only two meters to consider, one told him when he was on track, or how far he had deviated to left or right; the other told him how far he had to fly to reach his destination. An equipment meeting this requirement had already been flight tested, and further models were under construction.

It was not unwise to predict that within a year or two, it would be possible to present the pilot with an automatic map display of his position.

Afternoon Session:

THE CONSTRUCTORS' APPROACH TO THE PROBLEM

CAPTAIN H. A. MARSH (Chairman of the Helicopter Association) presided at the afternoon session. The idea of a full day's discussion on helicopters had originated with the Society, but it could hardly be a coincidence that all those who were invited to read papers were Founder Members of the Helicopter Association. The Association owed a big debt of gratitude to the Royal Aeronautical Society and other bodies for the help and guidance they had given in the three years since the incorporation of the Association.

During the afternoon session, papers would be presented giving the constructors' approach to the problems.

Dr. Bennett, who would describe the Fairey Gyrodyne, had specialised for the past 18 years on rotary wing development. He had worked with the late Senor de la Cierva and was largely responsible for the aerodynamics of the early Weir single-seater Autogiros and the direct take-off Cierva Autogiro. He was now Head of the Rotorcraft Division of the Fairey Aviation Company.

Mr. Hafner, who would describe the Bristol 171, had been solely engaged on rotary wing development for more than twenty years, having produced his first helicopter design in Austria in 1927. He came to England in the early '30's and continued with helicopter development, and had then turned his attention to the design and construction of a gyroplane known as the A.R.3. During the early part of the late war, he had collaborated with Dr. Bennett on various rotary wing projects under the Ministry of Aircraft Production, and had joined the Bristol Aeroplane Company as Chief Designer of the Helicopter Division in 1944, in which capacity he was entirely responsible for the design of the Bristol 171.

Mr. Shapiro, who would describe the Cierva Air Horse, had had varied experience in the design of ancillary aircraft equipment in France before coming to Great Britain in 1940. He was then for a time with Power Jets Ltd., after which he had had further experience on the design of aircraft instruments and power-assisted aircraft controls. In 1943 he had joined the Cierva Autogiro Company and was now Senior Technical Officer to that firm.

The Fairey Gyrodyne

by

J. A. J. BENNETT, D.Sc., Ph.D., F.R.Ae.S.

1. THE GYRODYNE APPROACH

THE success of the helicopter to-day is primarily the result of a background of rotary wing experience covering many years of research into the problems of the gyroplane. This simple form of rotorcraft, proposed by Juan de la Cierva, was developed to a stage at which vertical take-off and landing were normal manœuvres and were no longer exclusive features of the helicopter. Only the ability to hover remained as the unique advantage of the power-operated rotor—an advantage for which a heavy penalty had to be paid. The general problems of the helicopter for civil use are concerned mainly with an alleviation of the penalty that hovering has incurred.

The hovering requirement had led to the use of twin contra-rotating rotors, in spite of their greater complexity; to heavy disc loadings with their poor gliding performance; to rotors of high pitch, which require rapid action on the part of the pilot to prevent them from stalling in the event of power failure; to complicated devices for governing rotor pitch or engine speed arising from the need for control simplification; to an excessive forward inclination of the aircraft in forward flight; and to periodic blade-tip stalling, which had imposed a new limitation on top speed. In other words, the ability to hover could be bought at the expense of simplicity of control, safety, compactness of design, and comfort.

In the design of the Gyrodyne an attempt has been made to regain some of the ground that was lost. The propulsive powered rotor and the auto-rotative rotor represent two extreme forms of rotary wing aircraft, and the relatively non-propulsive rotor of the Gyrodyne avoids certain limitations of the two extremes. The possibilities of the Gyrodyne principle were discussed as long ago as 1940[1] and a description of the present machine (Fig. 1) was given in a recent lecture to the Helicopter Association.[2] It is

Fig. 1.
The Gyrodyne before take-off.

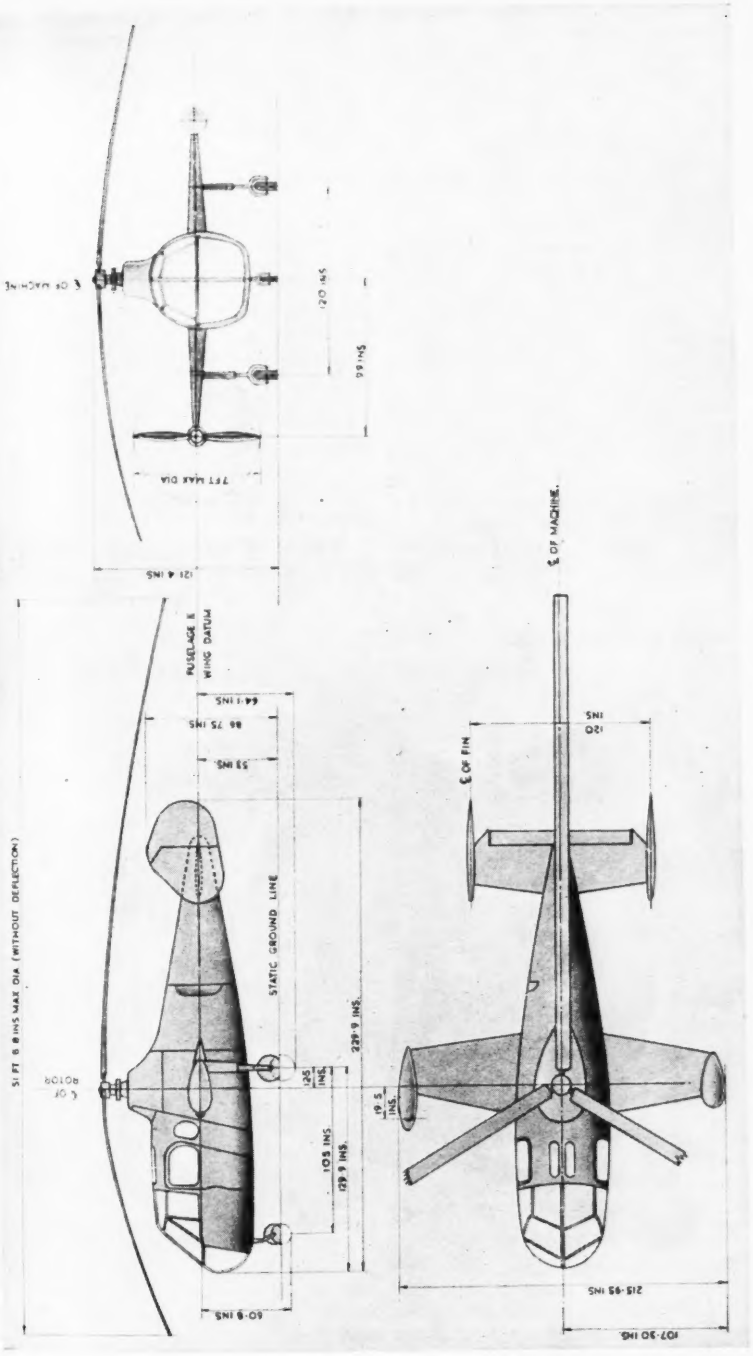


Fig. 2.
Principal dimensions.

proposed, therefore, to mention in this paper only those particular features of the Gyrodyne which have a bearing on the problems discussed by previous speakers.

2. COMPACTNESS OF DESIGN

In several respects the Gyrodyne configuration was the forerunner of the form of helicopter developed to a practical stage by Igor Sikorsky. Both utilise a single lifting rotor in torque balance with a single non-lifting airscrew; both have branch transmission systems of variable power distribution; and both obtain direct control in yaw from foot pedals, which vary the collective pitch of the non-lifting airscrew. The manner of operation of the two is therefore much the same, the main difference being one of degree only, in regard to control response. The Gyrodyne, because of its compactness of design, would be the more manœuvrable but for the stabilising surfaces at the tail.

Where the two differ in principle is in the azimuth location of the non-lifting airscrew and in its distance from the rotor axis. Taking into account the many uses for helicopters, it is thought that forward flight will occupy about 95 per cent. of the total life of the aircraft. An even higher percentage might apply to helicopters used only for transport. Consequently, if the non-lifting airscrew is located laterally, as in the Gyrodyne, the power required for torque balance is utilised for the useful purpose of forward propulsion throughout practically the whole of the normal operating life. On the other hand, with the non-lifting airscrew located at the tail, the power applied to it is a total loss under all normal operating conditions. To keep this loss at a minimum, the tail location requires a sacrifice of compactness, and this in general results in extra structural weight. There is no such requirement for the Gyrodyne.

3. LOW ROTOR POWER

The inevitable decrease in power loading of the propeller in forward flight decreases

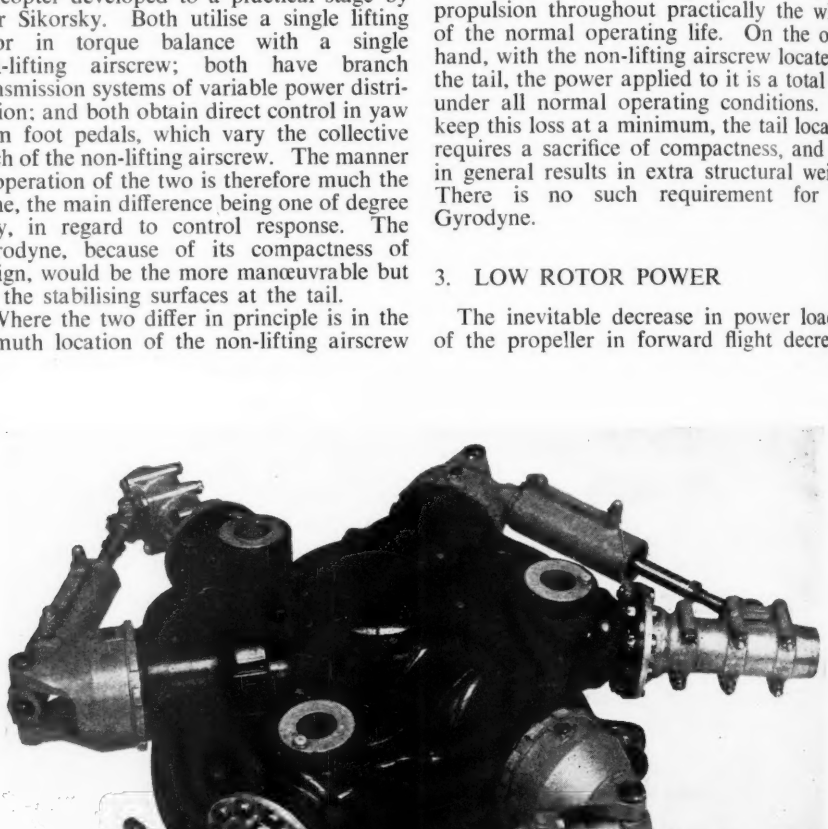


Fig. 3.
Rotor head.

the proportion of power delivered to the rotor as the forward speed increases. As a result, the main transmission of the Gyrodyne need be fully loaded only during the take-off and landing, thereby ensuring a high margin of safety at cruising speed, the normal condition of flight of a transport helicopter.

There are many uses for the helicopter where forward speed is unimportant and where the main requirement is to lift the maximum load that the available power will allow. For such duties, the non-lifting airscrew of the Gyrodyne might be moved farther outboard, but this need not be overdone at the sacrifice of compactness, because the Gyrodyne rotor can have a low disc loading and thereby lift the same load for less power than a rotor of high disc loading.

The relationship between the power x in the branch transmission of the non-lifting airscrew, per unit total power in both transmissions, and the distance a of the non-lifting airscrew from the rotor axis, expressed as a fraction of the radius of the rotor, is simply

$$x(1+6a)=1,$$

assuming a tip speed of 660 ft./sec. and a power loading of five for the non-lifting airscrew. If a is about one-third, as in the Gyrodyne (Fig. 2), x is also about one-third, or, in other words, two-thirds of the net power available, after allowing for engine cooling and transmission losses, is applied to the rotor.

In spite of the saving in structural weight gained by compactness of design and by the lower power requirement for the main transmission, and in spite of the low disc loading and better weight-lifting performance of the Gyrodyne rotor, it may be thought that too much power is applied to the propeller in vertical flight. This power, however, can be considered as a reserve and vertical climb can be boosted temporarily whenever necessary by the relatively simple expedient of performing axial turns.

Except at air displays, a helicopter need hardly ever climb vertically out of the "ground cushion." It is a much safer procedure to climb at the forward speed requiring minimum power and a steep angle of ascent at this speed is of greater importance in practice than a high rate of vertical climb. For take-off at altitude, a strong "ground cushion" is an advantage and this is assured by the low disc loading of the Gyrodyne.

Fig. 4.
Dual transmission system.

4. LOW DISC LOADING

Unrestricted by rotor blade clearance problems, the Gyrodyne has a lower disc loading than is possible with most other forms of helicopter. This gives the Gyrodyne certain advantages in both power-on and power-off flight. As the extreme limit of power loading of a rotor is equal to the reciprocal of the induced velocity, and the induced loss at take-off is roughly twice the profile loss, the limiting power loading of the helicopter is almost inversely proportional to the square root of the disc loading. Thus, if the disc loading of the Gyrodyne is 20 per cent. less than that of other helicopters of equal gross weight, the Gyrodyne rotor can lift the same load for 10 per cent. less power. This factor is mainly responsible for the low rotor power required in the Gyrodyne, the load sustained per rotor h.p. probably exceeding that of any other helicopter.

A similar advantage is obtained in power-off flight. The low disc loading minimises the sinking speed in a glide and ensures the safety of the occupants in an emergency landing. Even at night, or in a forced landing

because of fog a helicopter of low disc loading could descend and land almost vertically without disastrous results. The use of pitch change for utilising the kinetic energy of the rotor for momentary hovering prior to a power-off landing should be considered as an additional safety measure in helicopters, rather than a necessary manœuvre upon the precision of which alone the safety of the aircraft depends.

There is a general impression that a low disc loading, like a low wing loading for aeroplanes, is detrimental to efficiency at cruising speed. This is not necessarily so because it is not disc loading, but blade loading, that governs the profile power loss. The blade loading, being the ratio of the disc loading to the solidity, can be kept relatively high by choosing a low solidity. In the Gyrodyne, the solidity is only one per cent. per blade and the blade loading is 75. The high blade loading ensures a low profile power loss at top speed, and the low disc loading a low induced power loss when hovering.

5. LOW PITCH

There is no doubt that low disc loading and low rotor pitch contributed to the remarkable record of safety achieved by rotary-wing aircraft in the pre-helicopter era. In contrast to most other helicopters, a result of the low-pitch operation of the Gyrodyne is that it cannot be stalled under any condition of flight by a possible misuse of the controls.

Apart from safety, low pitch has other advantages, not the least of which is its effectiveness in minimising vibration—the "bugaboo" of rotary-wing aircraft. Helicopters which are rough in operation at high pitch in forward flight, are usually quite smooth at the same forward speed in autorotative flight.

The necessary rotor power for sustentation is absorbed in the Gyrodyne by its relatively high tip speed and, because the tip path plane is never tilted excessively forward for propulsion, the rotor remains at low pitch over the whole speed range.

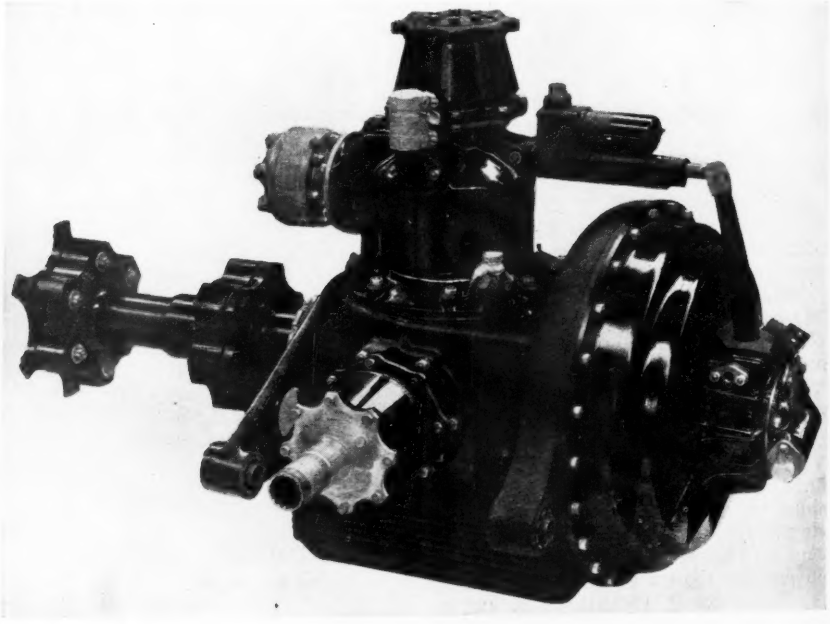


Fig. 5.
Main gearbox.

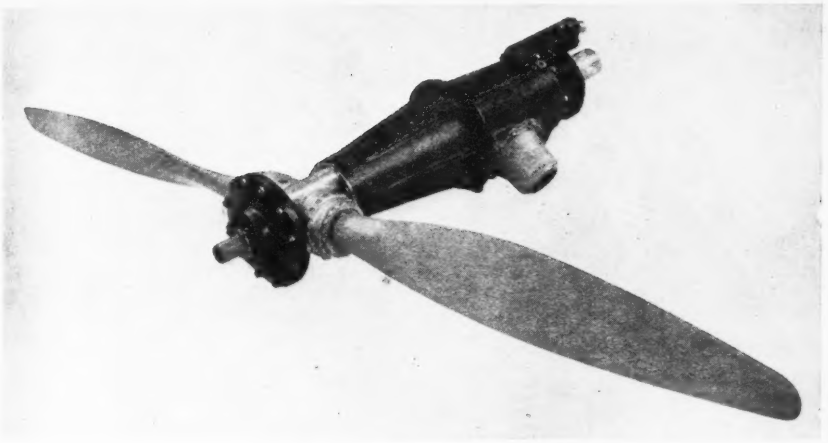


Fig. 6.
Outboard gearbox and propeller.

6. INDEPENDENT PROPULSION

A significant feature of the Gyrodyne is its independent means of propulsion. It enables both the fuselage and the tip path plane to remain substantially level under cruising conditions. This attitude is not only the optimum one in regard to drag and passenger comfort, but removes what had become an important barrier to the propulsion of helicopters.

Periodic lift distribution in auto-rotative rotors had resulted in stalling of a part of the retreating blade near the root, but in the helicopter with a forwardly-inclined rotor, periodic stalling can occur at the blade tip. This is caused by the relative air speed having a down-flow component. Operation of the helicopter close to the periodic stall of the retreating blade is limited by vibration. No matter how much power is available,

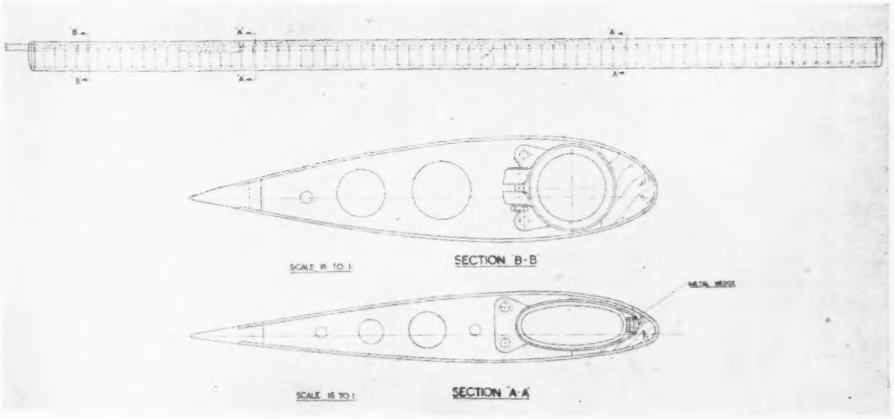


Fig. 7.
Rotor blade construction.

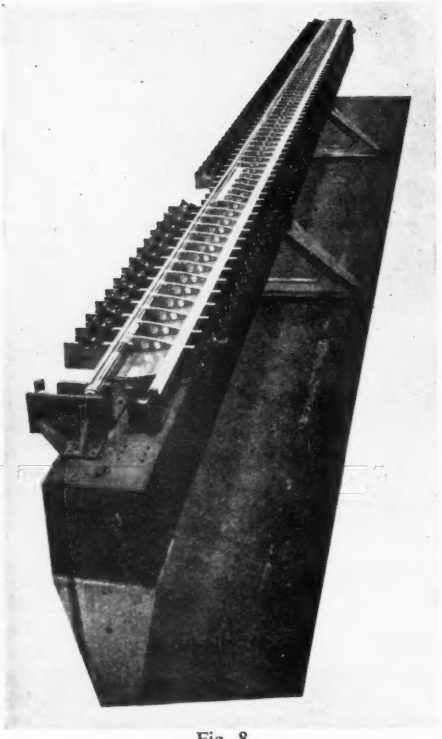


Fig. 8.
Jig for blade manufacture.

therefore, it cannot be utilised for propulsion beyond the periodic tip-stall barrier.

The international speed record for helicopters, now held by the Gyrodyne, can undoubtedly be exceeded in future by helicopters with propulsive rotors but, as higher-powered helicopters become available, the feature of independent propulsion as demonstrated in the Gyrodyne will become more and more essential.

There are many sources of vibration inherent in rotary-wing aircraft, but the periodic blade-tip stall is one which can be avoided and should not now prevent a further improvement in the helicopter speed range. Continuity of operation under adverse wind conditions is just as important for transport helicopters as for aeroplanes and can be ensured only by the ability to maintain a high cruising speed.

7. CONTROL SIMPLIFICATION

The simplicity of control of rotary-wing aircraft has deteriorated with the change-over from the auto-rotative rotor to the powered-rotor. The number of controls has been increased from two to four, and the ever-present necessity for torque balance and pitch-throttle synchronisation requires that the four controls be operated simultaneously. The inter-dependence of so many controls, requiring continuous manual adjustment by

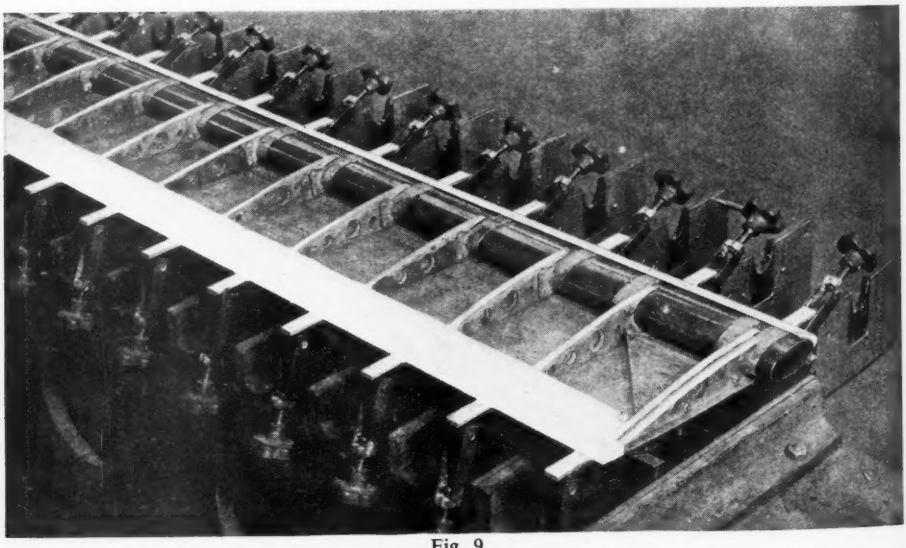


Fig. 9.
Outer portion of blade showing oval spar section.

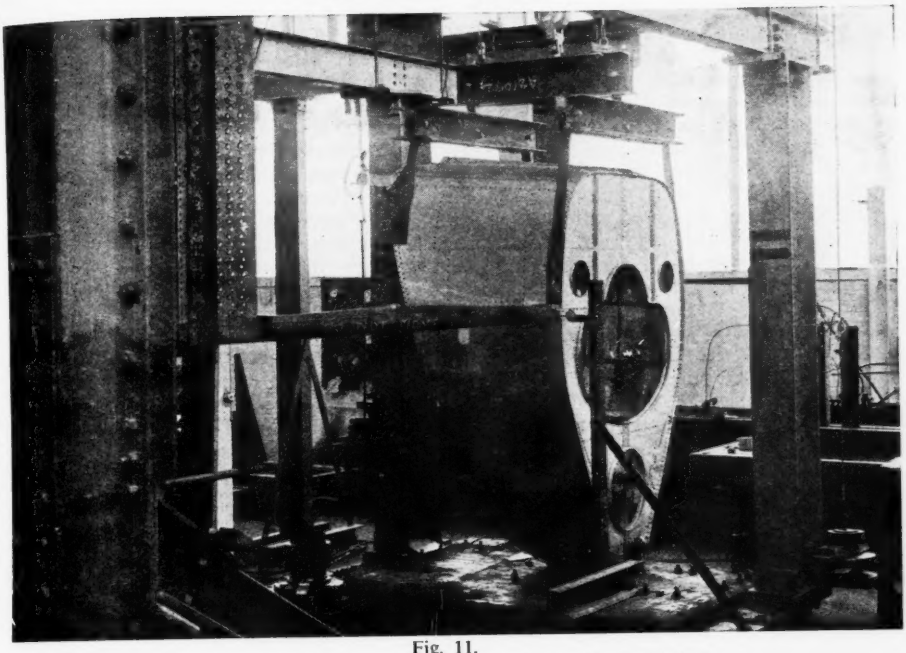


Fig. 11.
Centre section of production fuselage under static strength test.

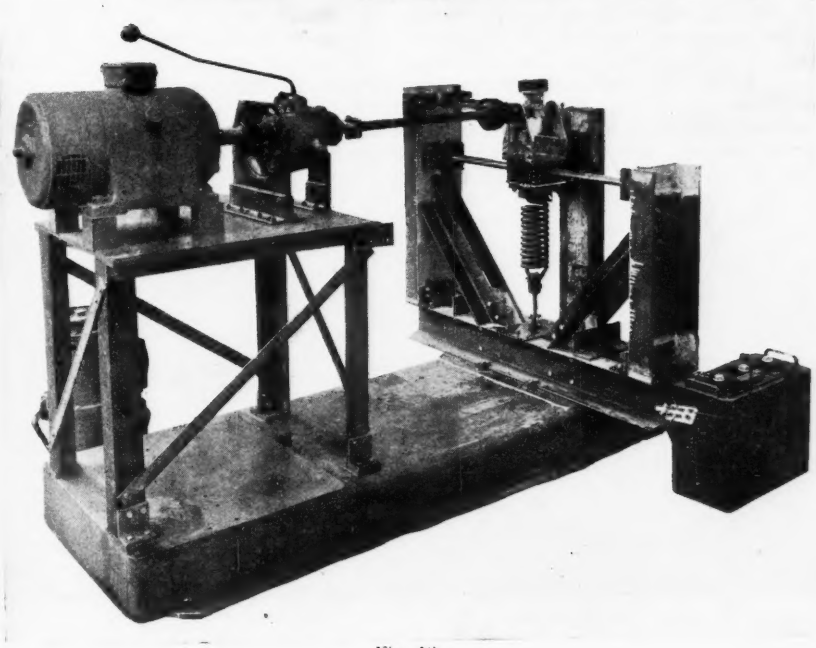


Fig. 10.
Rotor spar fatigue tests.

the pilot, is a further penalty that has been paid for the ability to hover.

In the Gyrodyne an attempt has been made to minimise this penalty by the suppression of one control. There are no flight controls other than stick, throttle and foot pedals, collective pitch change being effected automatically. The required automatic change in blade angle is associated with the angular displacement of the blade in azimuth in response to torque, by giving the drag hinge a slight downward and outward inclination. Thus, there is an immediate increase in manifold pressure whenever the throttle is opened without there being any appreciable change in angular speed. In addition to the automatic change of collective pitch, an over-riding control, mainly for trim purposes at altitude, has been designed, but is not yet installed. It is proposed to utilise this also for momentary hovering before a power-off landing. The over-riding device operates additional blade hinges which are locked in normal flight.

A further penalty in the helicopter has been the introduction of blade torsional bearings for both collective and cyclic control of pitch. In the Gyrodyne such bearings are eliminated entirely, and instead of a separate swash-plate for transmitting control movements from the stick to each individual blade through the necessary levers and bearings, the rotor head itself (Fig. 3) forms the swash-plate.

This does not mean that the hub axis is tilted, as was the usual practice with autorotative rotors. Instead, the hub axis, *i.e.* the axis of the main bearings, remains fixed and the rotor head—the hub member to which the blades are attached—is tilted with respect to the hub axis. Consequently, in forward flight a forward inclination of the head balances the backward inclination of the tip path plane that results from the usual flapping motion of the blades. The tip path plane, therefore, remains substantially at right angles to the hub axis in all conditions of steady flight, which is important for minimising vibration.

8. SAFETY MEASURES

Stick shake is completely eliminated by the use of hydraulic irreversibility. Except during the first few hours of flight, the steady loads also have been suppressed hydraulically, but it is now considered more desirable to retain the steady loads, which provide a natural feel, and to use hydraulic irreversibility only for suppressing stick shake and as a precaution against misuse of the control. A sudden backward movement of the stick in flight, for example, can impose on helicopters loads in excess of their design criteria.

A similar possibility exists in helicopters on initial engagement of the clutch and, in the Gyrodyne, to ensure that the rotor blades cannot be damaged by a sudden angular acceleration, an electrically-operated actuator is provided for controlling the rate of clutch engagement, thus limiting the maximum starting torque. It is thought that a torque-limiting device should be an essential airworthiness requirement for helicopters.

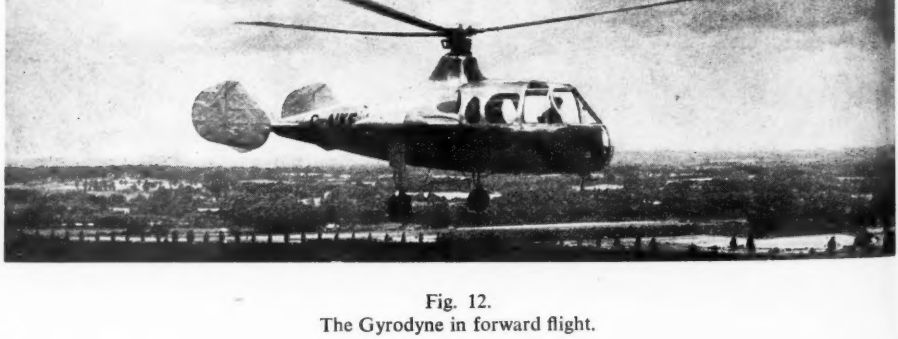


Fig. 12.
The Gyrodyne in forward flight.

9. TRANSMISSION FEATURES

The installation of the power plant and transmission (Fig. 4) consists of four self-contained units: the Alvis engine with its mounting and cooling system; the main gearbox (Fig. 5) incorporating the clutch and freewheel in addition to the first stage reduction gears for the rotor and propeller drives; the top gearbox, housing a double epicyclic gear, with a rotor brake mounted above it; and at the outer extremity of the starboard wing, a gearbox (Fig. 6) carrying the propeller reduction and pitch-changing gear. The propeller is positively geared to the engine and not to the rotor.

10. FREEDOM FROM FLUTTER AND FATIGUE

The rotor blades are of accentuated flexibility in bending, but rigid in torsion. On no occasion has there been any sign of flutter, although a Mach number of 0.8 has been exceeded at the advancing blade tip. The blades have been manufactured to close tolerances in a jig (Fig. 7) and, with this object in view, they have been given no taper or twist. A stiff profile is maintained by wooden ribs (Fig. 8) and a plywood covering, a steel tubular spar being the main strength member. This is circular in section at the root end, but over the greater part of its length it is of oval section (Fig. 9). A root collar integral with the spar—a Seefab development—enables the blade to be attached to the root fitting without stress concentration due to perforation of the tube. Drilling of the spar is avoided also at the rib clips, which are attached frictionally over the main portion of the blade.

Strain gauge tests have been conducted in flight, and the steady and alternating stresses determined at four different stations along the blade. Specimen lengths of the spar, loaded to a greater stress than the corresponding parts of the blade in flight, have been placed in a fatigue-testing machine (Fig. 10) and subjected to alternating stresses several times greater than the highest recorded in flight. The spar has thus been proved to have an unlimited life.

11. FUSELAGE STABILISATION

Although the present fuselage is of steel-tube construction, a metal monocoque is being provided for production (Fig. 11). The front portion is long enough to take a full-size stretcher, and as the tail portion is relatively short, side fins are required for directional stability.

No attempt has been made so far to provide dynamic stability at zero forward speed. The necessity for automatic stabilisation of helicopters in the hovering condition depends upon whether the aircraft will be required to hover for long periods. As the Gyrodyne is designed primarily as a transport aircraft, its normal condition of flight is at cruising speed. It is, therefore, under cruising conditions that stability is important and for this purpose a tailplane is provided in addition to the side fins. The stub wings, which form fairing surfaces for the structure supporting the propeller and the main legs of the tricycle undercarriage, have a stabilising effect in roll —a manœuvre in which rotary-wing aircraft tend to be too sensitive, compared with aeroplanes, because of the absence of fixed wings.

12. SPECIFIC UTILISATION

In any field of transport, no one device has a monopoly of all functions. Each type is a solution of a particular transportation problem. The advent of the helicopter, for example, does not put an end to the aeroplane, but confines its operation to uses for which it is better adapted. So also, every form of helicopter has its own specific sphere of usefulness, and the obvious one for the Gyrodyne is wherever a high cruising speed is essential, or continuity of operation is required under adverse wind conditions. Thus, the Gyrodyne is best adapted for making long non-stop journeys, such as from city centre to city centre, rather than as a feeder-line transport for operating only between a city centre and its adjoining airport.

If the ability to hover has been combined effectively with the ability to maintain a high cruising speed, without there being an appreciable departure from the low disc loading and low-pitch advantages of the auto-rotative rotor, the Gyrodyne has achieved its purpose and fulfils the general requirements of a helicopter intended for civil use.

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The Bristol 171 Helicopter

by

R. HAFNER

INTRODUCTION

THE technical problems confronting the helicopter designer are clearly enumerated in Captain Liptrot's paper, and Wing Commander Brie has drawn attention to a number of considerations of importance to the operator.

With some of these problems I have dealt in an earlier paper,[1] and to avoid repetition I propose to leave out points which have already been raised.

NOTATION

A_o, A_1, B_1, A_2, B_2 = Fourier coefficients expressing the rotor blade feathering motion.

$$\theta = A_o - A_1 \cos\psi - B_1 \sin\psi - A_2 \cos 2\psi - B_2 \sin 2\psi + \text{higher terms.}$$

R = rotor radius.

μ = tip speed ratio $= V/R\omega$.

V = aircraft forward velocity.

ω = rotor angular velocity.

$\mu_{(\text{lim})}$ = practical limit of tip speed ratio, where the higher harmonics of the feathering motion become appreciable.

$C_{L_{\text{basic}}}$ = lift coefficient of a rotor blade during hovering, referred to the rotor speed and blade area.

ρ = air density.

r = intermediate blade section position, measured from the hub towards the tip.

C_L = lift coefficient of rotor blade in forward flight.

F = factor expressing C_L in terms of $C_{L_{\text{basic}}}$ ($C_L = F \times C_{L_{\text{basic}}}$).

τ = intermediate blade section position expressed as a ratio of the rotor radius ($\tau = r/R$).

$C_{L_{\max}}$ = maximum lift coefficient obtainable before stalling occurs.

V_T = blade tip speed $= R\omega$.

$V_{T_{\min}}$ = minimum blade tip speed when $C_{L_{\text{basic}}} = C_{L_{\max}}$

$V_{\lim(\mu)}$ = limiting aircraft translational speed due to stalling of the retreating blade.

$V_{\lim(M)}$ = limiting aircraft translational speed due to critical Mach number for aerofoil section near the tip (advancing blade).

ϵ_p = profile drag/lift.

$C_{D_{\min}}$ = minimum profile drag coefficient.

ψ = blade azimuth angle, measured from downwind position, in the direction of motion.

v_n = velocity normal to the plane instantaneously containing the rotor blade.

v_{eff} = velocity in the plane, instantaneously containing the rotor blade, perpendicular to the longitudinal axis of the blade.

D_L = lift component in the plane of rotation.

L = blade lift.

λ = ratio of axial speed of rotor/tip speed.

ι = ratio of induced speed/tip speed.

ζ = factor for curvature of induced flow at the rotor.

β_o = rotor coning angle.

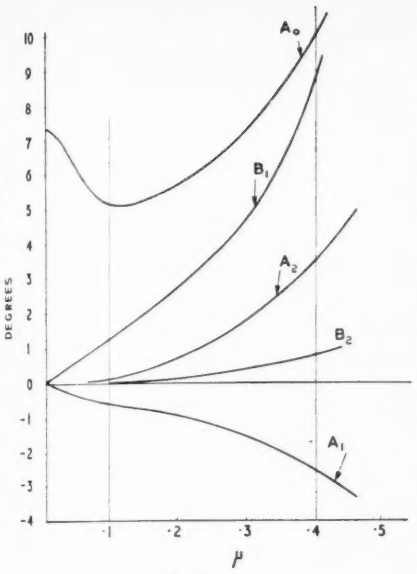

Fig. 1.

Fourier coefficients of feathering motion for conventional helicopter rotor in level flight.
$\theta = A_0 - A_1\cos\psi - B_1\sin\psi - A_2\cos 2\psi - B_2\sin 2\psi - \ldots$

VIBRATION

Rotating wing aircraft in forward flight are subject to vibrations for reasons which are fundamental and we must not expect the elimination of these symptoms, but only their reduction to generally tolerable proportions. We need more accurate methods of recording and analysing vibrations in helicopters in terms of component frequencies and amplitudes and, in addition, we must have generally agreed standards for comfort, *i.e.* limiting vibration levels as a yardstick both to makers and users of these aircraft.

As to the causes of rotor vibrations there is in the first instance a change of velocity with blade azimuth, the maximum being at the advancing and the minimum at the retreating, side of the rotor orbit; and secondly, a change of inflow angle with blade azimuth due to the coning of the rotor blade and the curvature of the air flow in the vicinity of the rotor, the maximum being aft and the minimum forward of the rotor centre. Therefore, in order to maintain a constant rotor thrust (or constant blade lift) during rotation, which is one of the essentials for freedom from vibration, the blade incidence must be varied in a cyclic manner.

Because the factors governing blade feathering are complex, the feathering motion cannot be expressed mathematically in a simple form but only by an infinite Fourier's series. Typical values for the Fourier coefficients A_0, A_1, B_1, A_2 and B_2 for a conventional rotor are given in Fig. 1 as a function of the tip speed ratio μ. A_0 represents the constant part of the blade incidence which can be obtained by the collective pitch control. A_1 and B_1 relate to the fundamental harmonic of the feathering motion which can be produced by a simple tilt of the control orbit with respect to the rotor orbit. The conventional swash plate or spider control or the tilting of the hub in an articulated rotor will produce this effect. The coefficients A_2 and B_2 relate to the second harmonic of feathering motion.

For small tip speed ratios these coefficients (and those of the higher harmonics) are negligible so that the conventional rotor control which can provide a simple sinoidal incidence variation during rotation, does satisfy to a fair degree the theoretical requirements. At larger tip speed ratios, the higher harmonics, which cannot be produced by the conventional control mechanisms, become predominant components. Thus at higher translational speeds the blade lift cannot be held constant any longer during rotation and vibration arises.

One can, of course, think of mechanisms which are capable of producing cyclic movements of a more complex form, including the higher harmonics. The mechanical elaboration involved in any such schemes, however, is considerable and, in my opinion, prohibitive and I regard as a practical limit for conditions of rotating wing flight the tip speed ratio μ_{lim} where higher harmonics just become noticeable.

The question arises thus. Can the Fourier coefficients be controlled by suitable design parameters and other means, with a view to suppressing the higher harmonics over as wide a range of μ as possible? As already mentioned, non-linearity and indeed discontinuities in the functions governing blade feathering are the principal causes for the higher terms, which I propose to discuss briefly.

The following assumptions are made:—

i. The resultant of the blade lift is acting at approximately $\frac{3}{4}R$

ii. The blade must be substantially free from stall outboard of this point.

If the mean lift coefficient during hovering[2] is

$$C_{L_{basic}} = \frac{\text{blade lift}}{\frac{1}{2}\rho\omega^2 \int_0^R cr^2 dr}$$

then the lift coefficient in translational flight can be shown to be

$$C_L = C_{L_{basic}} \times F$$

where

$$F = \left(\frac{1}{1+(\mu/\tau)\sin\psi}\right)^2$$

F reaches a maximum when the blade is retreating, *i.e.*

$$F_{(\psi=270^\circ)} = F_{max} = \left(\frac{1}{1-\frac{4}{3}\mu}\right)^2 \quad (\text{taking } \tau = \tfrac{3}{4})$$

and a limiting condition is therefore obtained when

$$C_L = C_{L_{basic}}\left(\frac{1}{1-\frac{4}{3}\mu}\right)^2 = C_{L_{max}}$$

or

$$\mu_{lim} = \tfrac{3}{4}\left(1 - \sqrt{\frac{C_{L_{basic}}}{C_{L_{max}}}}\right)$$

A high tip speed ratio can therefore be obtained only where the blade is flying at a low basic lift coefficient with an aerofoil capable of producing a high $C_{L_{max}}$.

The above expression can be written in another form

$$V_{lim(\mu)} = \tfrac{3}{4}(V_T - V_{T_{min}})$$

where $V_{lim(\mu)}$ = limiting translational speed (μ limit)

$V_T = R\omega$ = blade tip speed

$V_{T_{min}}$ = the minimum blade tip speed when $C_{L_{basic}} = C_{L_{max}}$

$V_{lim(\mu)}$ for the rotor of the Bristol helicopter 171 Mark 3 is given in Fig. 2 for various altitudes. In the same graph is similarly shown a high speed limitation $V_{lim(M)}$ which represents the critical Mach number for the aerofoil near the blade tip. An aerofoil with a low thickness/chord ratio (below 10 per cent.) is obviously desirable in this region, in order to delay shock stall.

The area within the limits shown in Fig. 2 can be utilised by the flight envelope of the rotor, which is, of course, subject to such additional limitations as may be determined by strength considerations or operating conditions of the power unit, and so on. The rotor flight envelope is defined in the cockpit by a very wide r.p.m. range for landing purposes which applies to speeds below 35 m.p.h., a smaller normal r.p.m. range applicable up to the speeds indicated on a special scale on the altimeter, and a narrow r.p.m. range applicable up to the maximum speed and for flight manœuvres involving high normal accelerations.

The above considerations relate to blade lift. In addition there is the problem of maintaining constant the force acting on the blade in the plane of rotation. This force is made up by the profile drag of the blade and a small component of the lift vector caused by the air flow through the rotor.

The profile drag of the aerofoils of the type used in rotor blades can be expressed by a single curve giving $\epsilon_p \frac{C_{L_{max}}}{C_{D_{min}}}$ as a function of $\frac{C_L}{C_{L_{max}}}$ where $\epsilon_p = \frac{\text{profile drag}}{\text{lift}}$ and which is shown in Fig. 3. Thus as C_L varies with ψ as the expression

$$C_L = C_{L_{basic}}\left(\frac{1}{1+\frac{4}{3}\mu\sin\psi}\right)^2$$

there will be accordingly a variation of profile drag during revolution. In the upper part of Fig. 3 are given as a function of μ the maxima and minima of F. From this can be obtained with the aid of the straight lines $\frac{C_{L_{basic}}}{C_{L_{max}}}$ the range of $\frac{C_L}{C_{L_{max}}}$ covered during revolution which in turn indicates the variation of ϵ_p.

This figure clearly shows the following significant features:—

(*i*) F_{max} increases very rapidly with μ while F_{min} decreases only moderately.

(*ii*) A very low "basic" lift coefficient will produce excessive drag at the advancing blade (F_{min}) and a high $C_{L_{basic}}$ excessive drag at the retreating blade (F_{max}). In view of the statement under (*i*) the latter is more likely to arise and therefore it is generally safer to fly at a low $C_{L_{basic}}$

(*iii*) A low $\frac{C_{D_{min}}}{C_{L_{max}}}$ is beneficial all round.

The component of lift in the plane of rotation D_L is dependent[1] on the inflow angle v_n/v_{eff}.

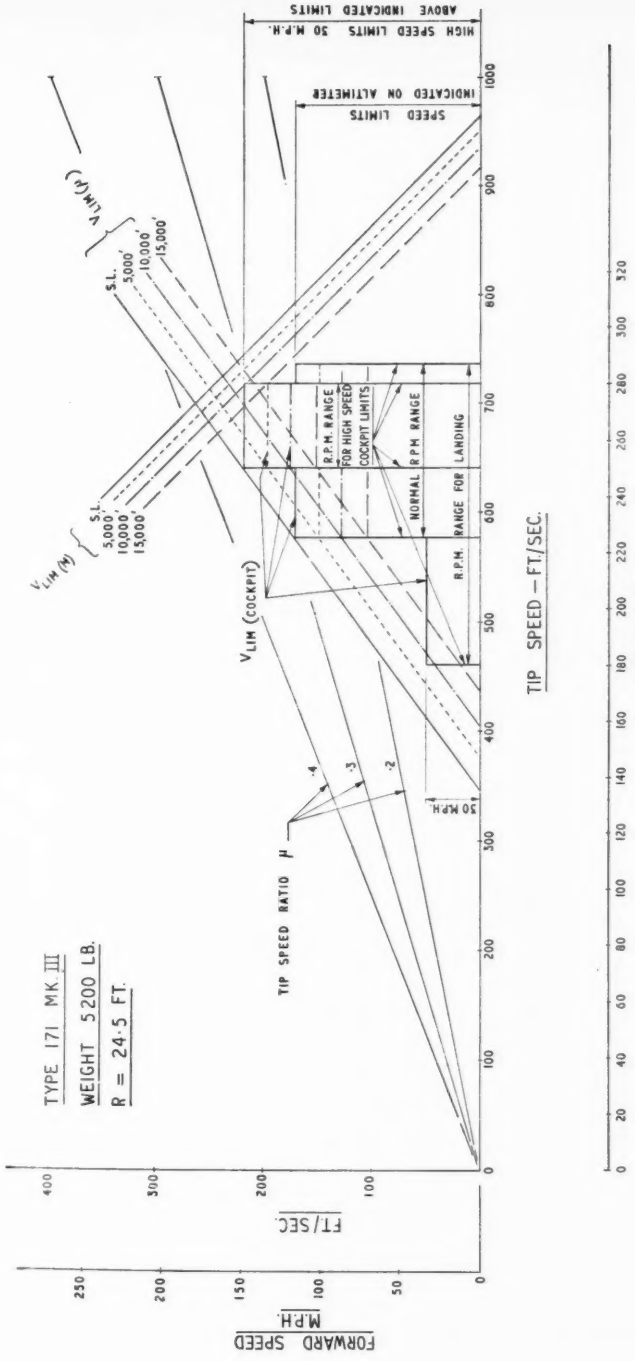
TYPE 171 MK. III
WEIGHT 5200 LB.
R = 24·5 FT.
FORWARD SPEED M.P.H.
FT/SEC.
TIP SPEED RATIO μ
V LIM (COCKPIT)
V LIM (M)
S.L.
5,000'
10,000'
15,000'
20 M.P.H.
R.P.M. RANGE FOR HIGH SPEED COCKPIT LIMITS
NORMAL R.P.M. RANGE
R.P.M. RANGE FOR LANDING
SPEED LIMITS INDICATED ON ALTIMETER
HIGH SPEED LIMITS 30 M.P.H. ABOVE INDICATED LIMITS
TIP SPEED — FT./SEC.
ROTOR R.P.M

Fig. 2.

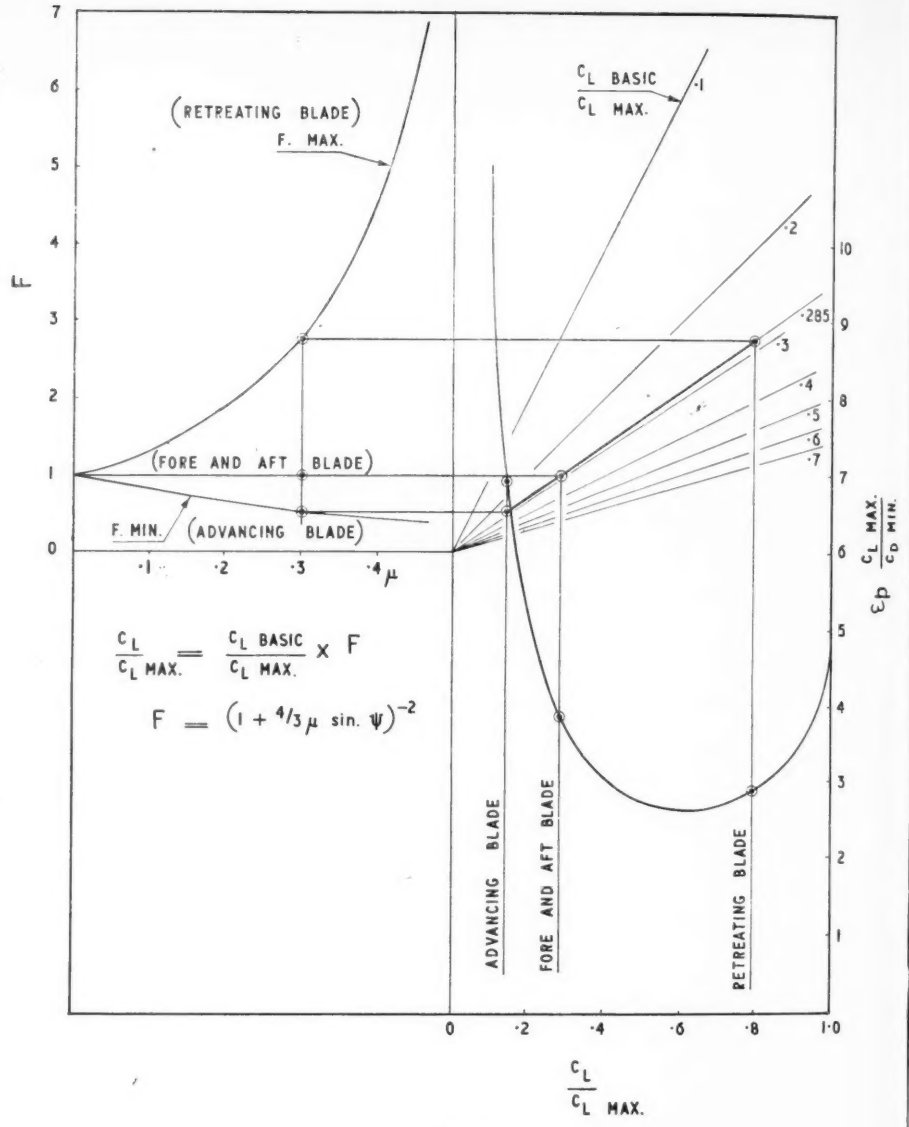

Fig. 3.

D_L = Blade lift $\times\, v_n / v_{eff}$

$$= L\left[\frac{\frac{4}{3}(\lambda+\iota)+\left(\frac{4}{3}\mu\beta_o+\zeta\iota\right)\cos\psi}{1+\frac{4}{3}\mu\sin\psi}\right]$$

where μ, λ and ι are the ratios between blade tip speed and forward speed, axial speed and induced speed at the rotor respectively.

ζ is a factor related to the curvature of the induced flow at the rotor. β_o is the coning angle of the rotor and $1/\tau$ has been taken to be 4/3. The above expression can be written as a series as follows:—

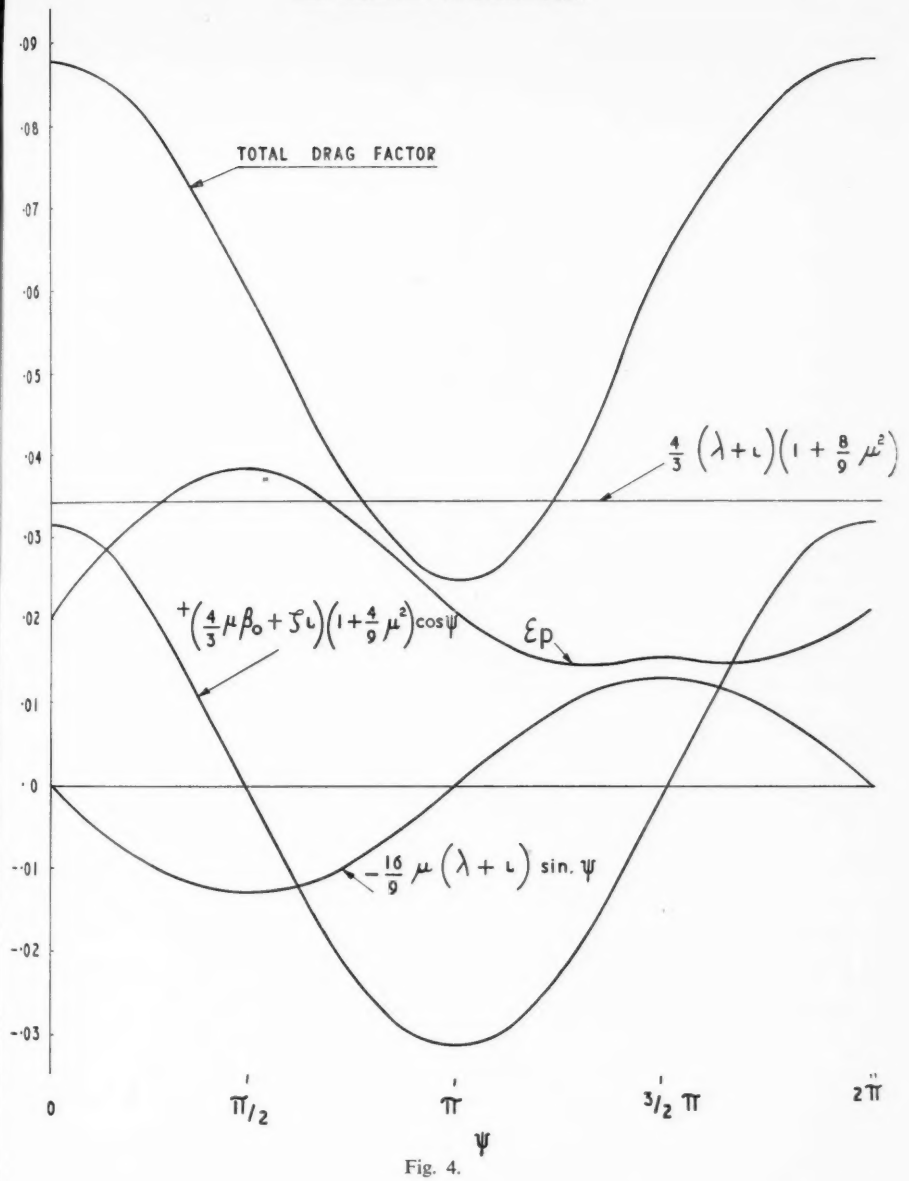

Fig. 4.

$$D_L = L\left[\frac{4}{3}(\lambda+\iota)\left(1+\frac{8}{9}\mu^2\right)+\right.$$
$$+\left(\frac{4}{3}\mu\beta_0+\zeta\iota\right)\left(1+\frac{4}{9}\mu^2\right)\cos\psi-$$
$$\left.-\frac{16}{9}(\lambda+\iota)\mu\sin\psi+\text{higher terms in }\psi\right]$$

In this only the first term is constant, the others change with ψ and thus represent varying forces. It is therefore desirable that the coefficients preceding $\cos\psi$ and $\sin\psi$ be kept as small as possible. μ, λ and ι can be reduced by increasing tip speed. λ moreover can be reduced by reducing the parasitic

Fig. 5.
The Bristol 171.

drag of the whole aircraft. Apart from such minor variations, λ in the pure helicopter is essentially an expression of flight condition of the aircraft, being necessarily larger in a climb than in level flight. In an auto-rotating rotor λ is always negative. ζ cannot be controlled materially by design.

In order to illustrate the above arguments the drag of a rotor blade of the Bristol type 171 is now analysed on the basis of the above formulæ.

Conditions of flight:—

Steady level flight at sea level.

Forward speed—136 m.p.h. = 200 ft. per second.

Rotor speed—260 r.p.m. = 670 ft. per second.

$\mu = .30 \quad \lambda = .02 \quad \iota = .0043 \quad \beta_o = .065 \quad \zeta = .8$

$$\frac{C_{L_{basic}}}{C_{L_{max}}} = \frac{.37}{1.30} = .285$$

$$\frac{C_{L_{max}}}{C_{D_{min}}} = 180$$

In Fig. 4 the various components of blade drag are plotted as a function of ψ and it is shown how by a suitable choice of design parameters the drag variation due to inflow conditions $(\lambda + \iota)$ can be counteracted by profile drag (ϵ_p). Where the latter is a maximum the former reaches a minimum and vice versa. This has been achieved by the use of a low "basic" lift coefficient giving an ϵ_p-curve variation in the form of a $+\sin e$ curve. On the other hand, had the "basic" lift coefficient been high then the ϵ_p-curve would have taken the shape of a $-\sin e$ curve, thereby amplifying the variation caused by $(\lambda + \iota)$. A low "basic" lift coefficient moreover represents a safety margin against stalling in accelerated flight conditions.

It will be seen, therefore, that variation of blade drag is mainly caused by blade coning. This variation, even with the exceptionally small coning angle of the Bristol 171 rotor, represents more than 50 per cent. of the total mean drag, which illustrates the importance of this design parameter. Under cruising conditions this drag variation is much more serious than the variation in blade lift referred to earlier.

The drag of all blades adds up vectorially to the total rotor force in the plane of rotation. Thus the more blades in a rotor the steadier will be this force, so that the three-bladed rotor, from the vibration point of view, is very much better than the two-bladed rotor which, as already mentioned earlier,[1] is only justified in the very small sizes. I have indicated also my preference for individual blade articulations over a

flexibly mounted rotor (except for small sizes), as well as certain features in blade design, such as careful distribution of blade mass radially as well as chordwise and a high torsional stiffness. The ideal blade tapers from root to tip in thickness and plan form, and is of metal monocoque construction.

CONTROLS

There is clearly a need for simplification of controls: more simplification in engineering generally means more efficiency and more safety. This argument does not apply to the *number* of flying controls in the cockpit, which is determined only by the degree of freedom of movement of the aircraft.[1] I am of the opinion that the conventional arrangement consisting of yawing control, rolling and pitching (or azimuth) control and vertical (or collective pitch) control, together with the rotor speed control represents an absolute minimum. There is ample opportunity for simplification in the mechanism of the control circuits and this has been made a fundamental feature in the design of the Bristol helicopter. It is noteworthy that the rotor control mechanism of this aircraft (starting with the three-blade levers and finishing with the dual azimuth and collective pitch control levers) consists of only 27 moving parts. The use of the tie rod in this helicopter is now well known and needs no further comment.

The design of cockpit controls is at present handicapped by the lack of agreement on control layout for helicopters. Standardisation of cockpit controls is an urgent need.

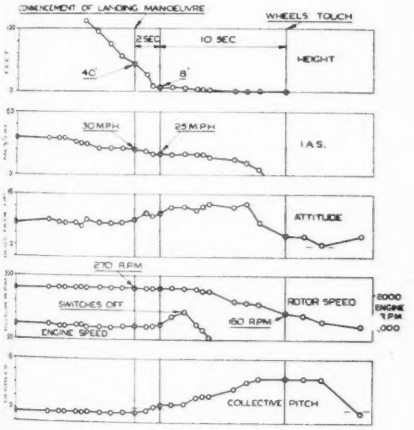

Fig. 6.
Auto-observer records of typical auto-rotating landing of Bristol Helicopter Type 171.

STABILITY

I propose to make only a few general observations on this subject. The stability of present-day helicopters is far from satisfactory and "the" solution of the problem, which must be simple as well as adequate, does not appear to be around the corner yet.

There are two distinct types of stability, distinct from the theoretical as well as the pilot's point of view:—

(*a*) *Stability in forward flight*

In this respect the helicopter does not differ materially from the fixed-wing aircraft. Most of the flying time is accumulated in forward flight and positive stability in this condition will prevent pilot's fatigue and therefore, increase safety.

(*b*) *Hovering stability*

The hovering stability is based on different principles and is more difficult to obtain than stability in translational flight. As hovering flight is done in circumstances when concentration on the part of the pilot is needed in any case because of the proximity of the ground, or the need to remain in a given attitude with relation to a fixed point, and the time spent in this condition is comparatively short, there would not seem to be the same need for positive hovering stability as for positive forward flight stability. If the latter is fully achieved while in hovering the aircraft is not unduly unstable, in my opinion a good advance is made towards the ideal.

The Bristol type 171 shows in forward flight a fair measure of positive stability in

pitch, yaw and roll and has been flown in gusty air for extended periods without touching any of the controls. Minor displacements are damped out and only severe gusts require corrective action on the part of the pilot. This has been achieved mainly by a fuselage carrying a small tailplane outside the rotor disc and a rotor with a large moment of inertia providing damping in pitching motion.

SAFETY

Apart from structural and mechanical safety an important safety criterion is the emergency landing in the event of power failures. While the rotative wing is reputed to offer a high measure of safety in auto-rotative descents, recent reports have drawn attention to so-called "danger zones" from where an auto-rotative landing could not be made without damage to the helicopter. The vertical velocity of a conventional helicopter during auto-rotative descent, especially at low forward speeds, is too great to be absorbed by the undercarriage and must therefore be "checked" before landing by momentary increase of rotor lift, which involves a certain amount of energy. In the absence of engine power such energy is available in the form of kinetic energy from the horizontal velocity component of the aircraft, as well as from the rotational velocity (useful r.p.m. range) of the rotor. When these two sources of kinetic energy are insufficient to provide the required "check" then damage will result on landing.

In order to eliminate this hazard, the rotor of the Bristol helicopter has been designed deliberately to give a high rotational moment of inertia in conjunction with an unusually wide r.p.m. range. The kinetic energy which is stored in this rotor at maximum permissible rotor speed is 680,000 lb. ft., which represents an amount of work equivalent to about four seconds hovering in the ground cushion at full load. Many landings have already been made with this aircraft with its engine switched off, which have indicated an ample supply of kinetic energy during the landing manœuvre.

Auto-observer records of such a landing are reproduced in Fig. 6. The steady conditions during the auto-rotative descent before the landing manœuvre appear to be as follows:—

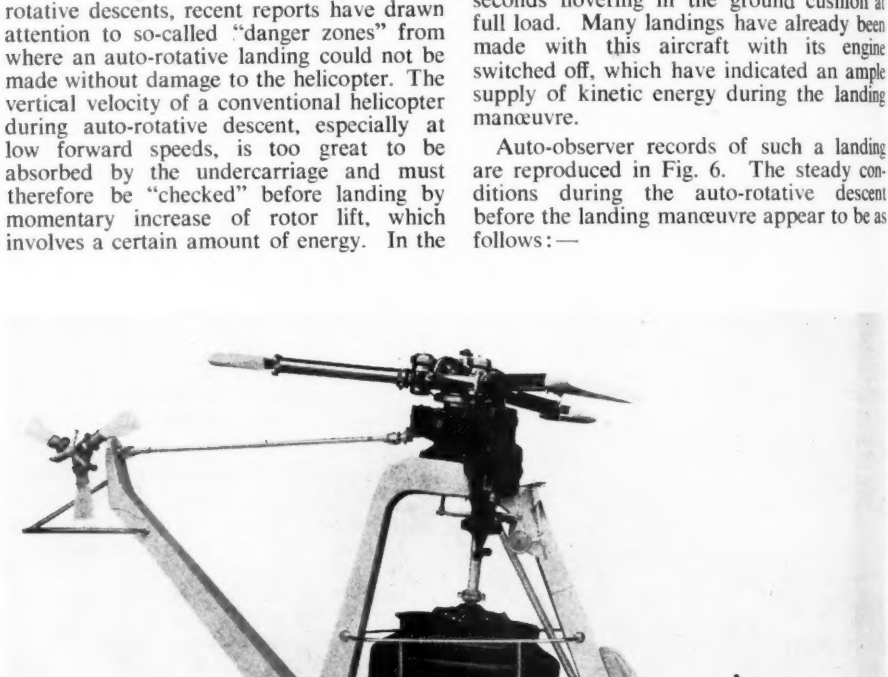

Fig. 7.

Rate of descent	...	1,600 ft./min.
I.A.S. ...	...	35 m.p.h.
Rotor speed	...	270 r.p.m.
Engine idling		
Collective pitch	...	0 degrees
All-up weight	...	4,740 lb.

At about forty feet from the ground the collective pitch is increased slightly and the engine switched off. This results, after about two seconds, in a checking of the descent at a height of approximately eight feet, and a reduction of forward speed by some five miles per hour. During the following ten seconds the aircraft sinks slowly until, at first the tail skid, and then the wheels, touch down. During this period the collective pitch is steadily increased to 11°, the rotor speed drops to 160 r.p.m. and the forward speed down to walking pace. Apart from an aft movement of the control column at touch-down, all controls remain substantially stationary. This serves to show that with sufficient kinetic energy and good control, an "engine off" landing can be made in safety and comfort, even with a heavy helicopter.

CAPITAL AND MAINTENANCE COSTS

One of the main arguments against the helicopter is that it is expensive to buy and an excessive amount of time and money is spent on its maintenance.

The helicopter of to-day is expensive to buy not for reasons peculiar to this type of aircraft, but simply because the market to-day does not justify production on a large scale, without which a material reduction of price cannot be achieved.

Maintenance costs can be reduced if the following design principles are adhered to:

1. Mechanical simplicity and economy in the number of moving parts.
2. Fatigue resistance and high life factors in parts subject to cyclic forces and to wear.
3. Accessibility.
4. Interchangeability.

Figure 7 shows the entire mechanical assembly of the Bristol 171 helicopter which comprises the power unit with clutch, cooling fan, and cowlings, the main rotor gearbox and hub carrying the main rotor blades, the tail rotor gearbox and hub carrying the tail rotor blades and transmission shafts between these units and in addition, the rotor controls. The extreme simplicity of this layout is evident.

It has been possible to design all wearing parts for a life of 7,500 hours without great sacrifice in weight. This feature, apart from beneficially affecting the safety of the aircraft, it is hoped will eventually permit the periods between overhauls to be increased to 1,000 hours or more (excepting the power unit) which not only simplifies maintenance but ensures that the adjustment of wearing parts is left undisturbed over long periods, which allows these parts to "run in" under ideal conditions.

Fatigue is one of the topics in aircraft engineering. There is no royal road to endurance and a long and generally arduous test and development programme with the proverbial, "exploring of every avenue and leaving no stone unturned" which involves a great amount of test equipment and cost is the only real safeguard against fatigue failures. Special testing equipment which has been developed in conjunction with the type 171 has been discussed in an earlier paper.[1]

The principle of interchangeability is applied generally. Originally we hoped to build individually interchangeable rotor blades which were to be balanced dynamically as well as aerodynamically against a master blade, but experience to date has indicated that blades can be assembled satisfactorily only in rotor sets. In the event of damage to one blade in a rotor, however, this does not imply the scrapping of the remaining good blades which can be "paired" with others to make up new rotors.

ACKNOWLEDGMENTS

My acknowledgments are due to the Ministry of supply and the Bristol Aeroplane Co. Ltd., for permitting the publication of information relating to the Bristol helicopter type 171.

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The Cierva Air Horse

by

J. S. SHAPIRO, Dipl.Ing, A.F.R.Ae.S.

I. THE MACHINE

1. ORIGINS OF THE THREE-ROTOR CONCEPTION

FIGURES 1 and 2 show external views of the Cierva Air Horse.

The Air Horse design arose primarily as an answer to the demand for large loads. It was realised that difficulties in helicopter construction increased in proportion to rotor diameter and nothing was more natural than to increase the number of rotors. It is not surprising that three rotors were chosen.

A body in space is determined by the position of three of its points, provided that these are not in line. The three rotor conception, therefore, is natural and as such can be traced back to early origins. Fig. 3 shows "Barclay's improved aerial vehicle," from the specification of a patent granted in 1903 to a telegraphist in Basutoland. Apart from the three-rotor feature, there is little similarity with the Air Horse. We are getting a little nearer when we look at Fig. 4 showing a much more recent patent drawing from a specification of Florine (1921) which covers the torque compensation by rotor tilt in a co-rotating multi-rotor helicopter.

2. DISTINGUISHING FEATURES

Contrary to Florine's proposals, the Air Horse rotors have freely flapping blades but, in common with Florine's ideas, the rotors are rotating in the same direction and torque reaction is counteracted by horizontal thrust components. These are obtained through a built-in tilt of the rotors, mainly in the lateral sense.

This machine is further characterised by a single rotor being placed forward, in the normal direction of flight, with the remaining two rotors, in side-by-side formation, behind.

Fig. 1.

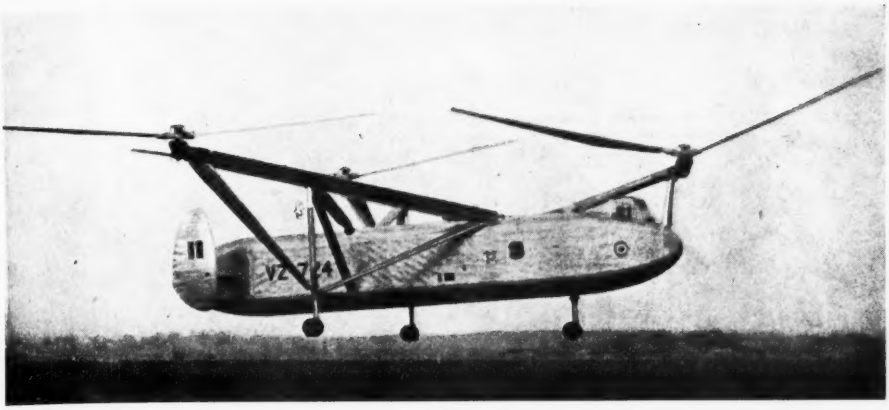

Fig. 2.

The Air Horse is controlled about its pitching and rolling axes by means of lift couples obtained through differential application of collective pitch to the three rotors in an obvious manner. For the purpose of control about the yawing axis, cyclic pitch variation in the fore and aft phase is applied differentially to the side-by-side rotors. The result is a virtual fore and aft tilt of the rotor discs, thereby establishing horizontal thrust components with a yawing couple between them.

Finally, the machine has an undercarriage with a stroke of five feet and is thereby enabled to absorb the shock of very high rates of descent.

3. DESCRIPTION

Figure 6 gives the principal data of the Air Horse.

In Fig. 5, showing the general arrangement of the machine, the main constructional features can be seen. The airframe consists of a semi-monocoque fuselage, starting with the cockpit section, fitted with fully duplicated controls and the necessary instruments and covered with a canopy of moulded perspex, allowing nearly unobstructed vision all round.

Behind the cockpit section there is a small load compartment to be used for luggage in the passenger-carrying machine. Through this the crew have access to the cockpit. The front undercarriage leg is attached to a fuselage frame at the rear of this compartment.

This compartment is followed by the engine section, which houses the engine and its accessories, the distribution gearbox, the "control exchange" mechanism with its ancillary hydraulic equipment, and the fan and radiator unit. A fire-proof bulkhead separates this section from the main load compartment, which at present is fitted for freight-carrying only.

Finally, a tail section completes the streamlining of the fuselage and is built in two halves, hinged for swinging, to allow unobstructed access to the main load compartment. The tail section carries a tail unit consisting of a fixed tailplane having twin orientable fins at its extremities.

The outriggers which carry the rotors consist of the front boom with its stabilising struts and the rear booms with their supporting structure king posted around the rear undercarriage legs. Booms and struts are of semi-monocoque construction and are streamlined to reduce forward drag.

The undercarriage legs consist of two sets of telescoping tubes each. The outer, large diameter tubes are used for load-carrying purposes only and the inner set constitutes the oleo-pneumatic shock absorber. The legs are supported by twin wheels chosen solely for their carrying capacity, as the helicopter has to be braked for parking only.

The power unit is a Rolls-Royce Merlin Mark 24 engine which is a single-stage two-speed supercharged version with built-in reduction gears. Fuel and oil systems are conventional. The cooling system is of the

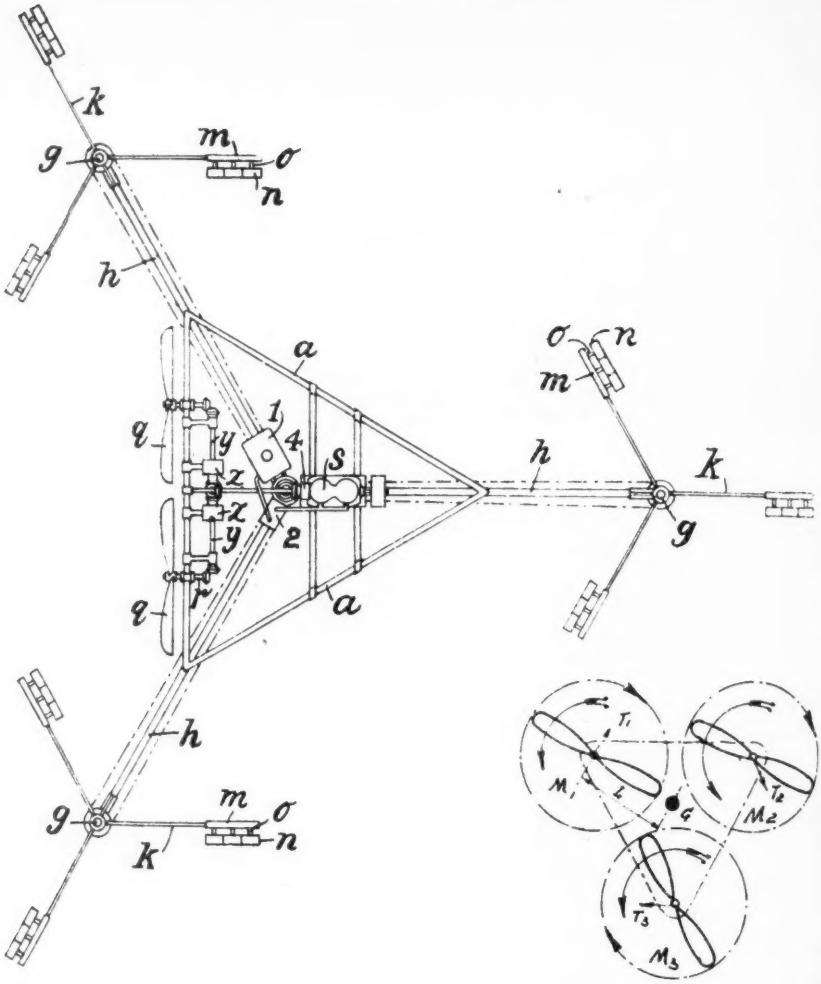

Fig. 3.

Fig. 4.

shunt layout and includes a light alloy radiator. The exhaust system is a specially developed "cross-over" manifold surrounded by a jacket through which cooling air is drawn by ejector action of the exhaust gas. Coolant radiator and oil coolers (including transmission oil cooler) receive a flow of air from a horizontally mounted variable pitch fan drawing air from above and ejecting it downwards through the radiators.

The engine drives the distribution gears through its standard spur gear reduction and a clutch unit consisting of two parallel branches. One branch is a manually released, centrifugally loaded, multi-plate friction clutch with a roller type free wheel in series. The other branch is a centrifugally released automatic clutch of the wedged roller type which engages when the rotor system reaches a certain speed of rotation and torque is transmitted from the engine. The friction clutch is released by a clutch lever operated by the pilot and engages provided that the engine has attained a minimum speed of rotation. Through the

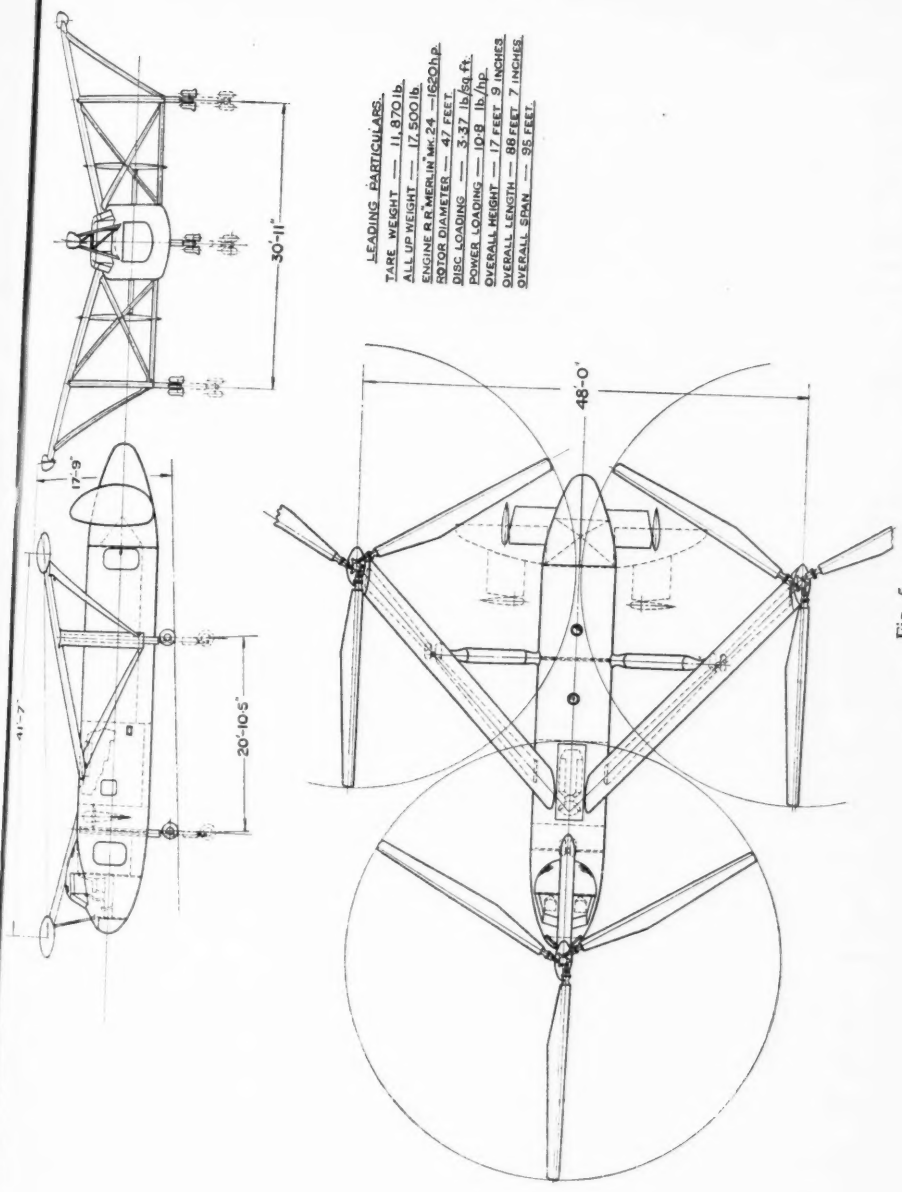
LEADING PARTICULARS.
TARE WEIGHT — 11,870 lb.
ALL UP WEIGHT — 17,500 lb.
ENGINE R.R. MERLIN MK. 24 — 1620 h.p.
ROTOR DIAMETER — 47 FEET.
DISC LOADING — 3.37 lb/sq. ft.
POWER LOADING — 10.8 lb./hp.
OVERALL HEIGHT — 17 FEET 9 INCHES.
OVERALL LENGTH — 86 FEET 7 INCHES.
OVERALL SPAN — 95 FEET.
30'-11"
17'-9"
41'-7"
20'-10.5"
48'-0'

Fig. 5.
G.A. of W.11 Air Horse.

friction clutch the rotor system is brought up to speed and thereupon the roller clutch engages automatically. This latter constitutes its own free wheel. In the event of engine failure, the rotors remain permanently geared together. The clutch unit incorporates the rotor brake manipulated by the clutch release lever.

The distribution gears split the power, without speed reduction, into three branches of transmission shafting. The shafts run through the outriggers to connect the distribution gearbox with the rotor gearboxes and consist of large diameter aluminium alloy tubes fully protected against deformation of the structure by means of universal joints and flexible couplings. The rotor gearboxes contain two steps of speed reduction, of which the first is a set of straight bevel gears and the second is an epicyclic gear train having straight spur teeth.

The hub spider (Fig. 7) is mounted on the epicyclic output shaft and includes integral flapping pins carrying flapping links on ball and roller bearings. The flapping axes intersect the axis of rotation.

The drag link is hinged through needle bearings on the drag pin situated at approximately 5 per cent. of blade radius and carries the torsional articulation consisting of one double action, preloaded, large diameter taper roller bearing. The drag link is restrained in its motion by hydraulic dampers.

The blades are of all-wood design, but attached with light alloy fittings screwed on to the spar. The main blade spar is made of high density, resin bonded, laminated wood. Pressure-moulded skins are checked into the main spar and cover the hollow trailing edge portion of the blade profile, but are supported by longitudinal auxiliary spars. The blades are of NACA 23015 Profile, tapered planform, and have an appreciable twist.

The flying control system consists of the pilot's control organs, the mechanical linkage, the "control exchange" mechanism, the hydraulic assister installation, the control transmission lines to the three rotors, and the hub control mechanism.

The pilot's control organs are arranged in a conventional manner and include: control column for pitching and rolling control; rudder pedals for directional control; and a pitch lever coupled with the engine throttle control, but having a throttle adjustment by means of a twist grip. These control organs act through a conventional linkage on the "control exchange" mechanism. This mechanism translates displacements of the control organs into appropriate combinations of displacements which are transmitted to the hub control mechanisms.

A flanged fitting, sandwiched between the rotor blade root adaptor and the torsional bearing housing, terminates in the blade control shaft which runs through the drag and flapping links and is universally joined, concentric with the drag hinge. This shaft carries the pitch arm, the extremity of which is linked to an arm of the hub control spider by means of an adjustable rod. Blade pitch, therefore, follows the movements of the hub control spider which consist of an axial movement actuated by the rotation of a sprocket below the rotor gearbox and

W11 PRINCIPAL DATA.

ALL UP WEIGHT	17,500 LB
EMPTY WEIGHT (FREIGHT CARRIER)	11,870 LB

ROTORS

NUMBER	3
DIAMETER	47 FT.
NUMBER OF BLADES PER ROTOR	3
NOMINAL SOLIDITY	0·0598
NOMINAL TWIST	11° 45′
NOMINAL TAPER	2·584 : 1
BLADE PROFILE	N.A.C.A. 23015
NOMINAL R.P.M.	219·5

ENGINE.

1 ROLLS-ROYCE - MERLIN - MK 24.
SUPERCHARGER. SINGLE STAGE TWO SPEED
GEAR RATIOS 8·15 : 1 AND 9·49 : 1

	BOOST	R.P.M.	I.C.A.N. SEA LEVEL H.P.
MAX. POWER (5 MIN)	+18	2,850	1620
CLIMB POWER (1 HOUR)	+12	2,850	1290
MAX CONTINUOUS POWER	+9	2,850	1120

PERFORMANCE

MAX. RATE OF VERTICAL CLIMB, I.C.A.N. SEA LEVEL CONDITIONS = 900 FT/MIN.

LEVEL FLIGHT SPEED FOR MAX CONTINUOUS POWER I.C.A.N. SEA LEVEL CONDITIONS = 125 M.P.H

Fig. 6.

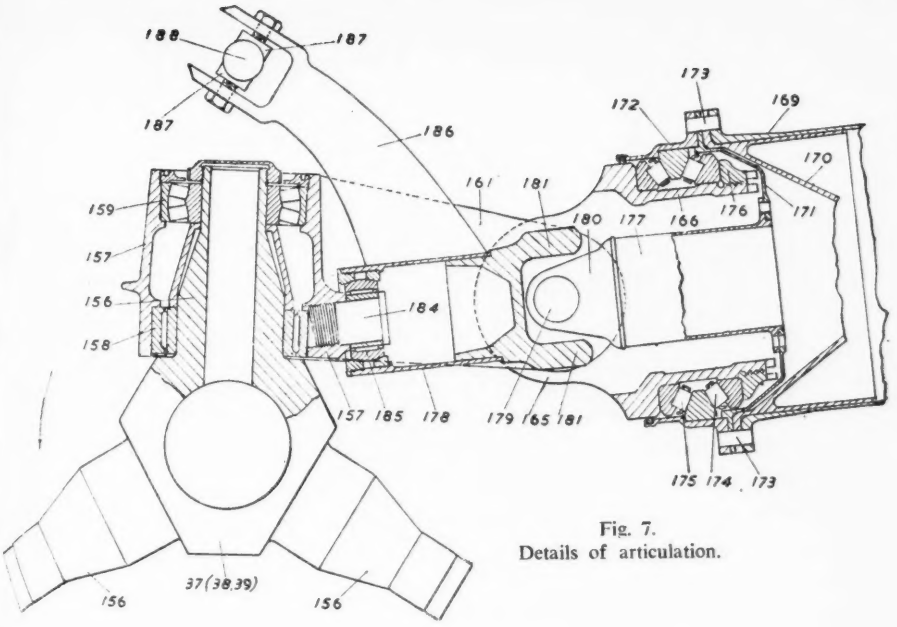

Fig. 7.
Details of articulation.

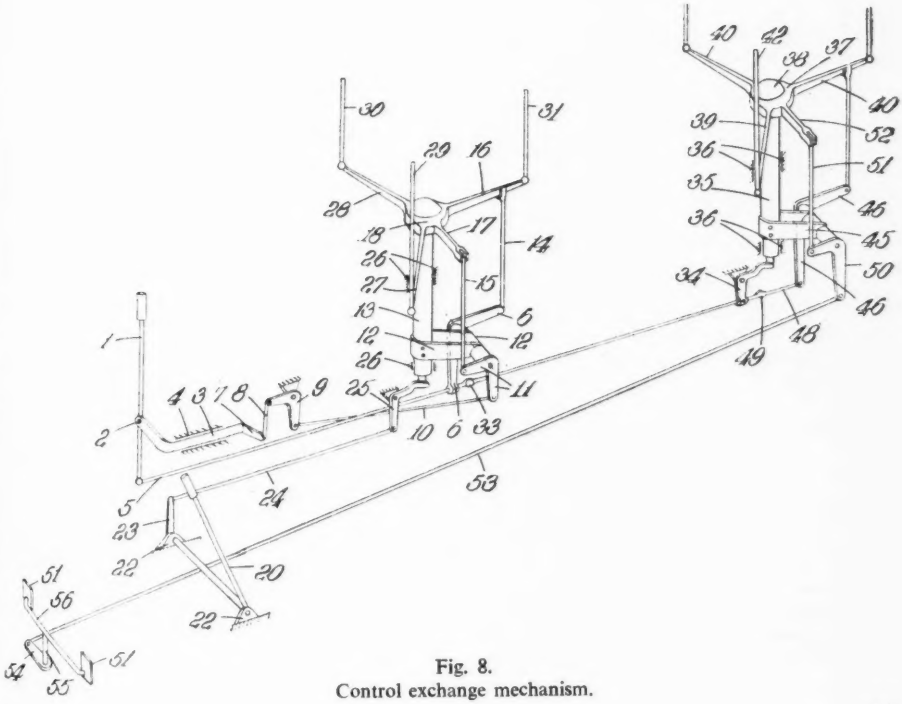

Fig. 8.
Control exchange mechanism.

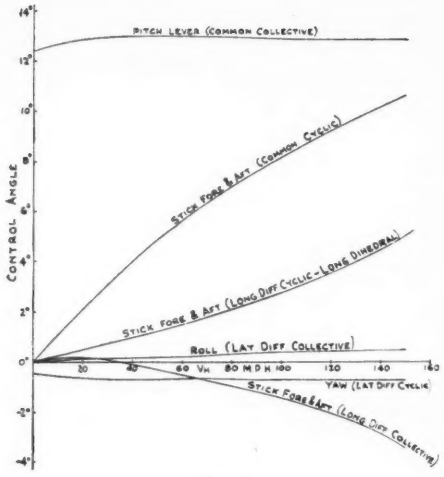
PITCH LEVER (COMMON COLLECTIVE)
STICK FORE & AFT (COMMON CYCLIC)
STICK FORE & AFT (LONG DIFF CYCLIC - LONG DIHEDRAL)
ROLL (LAT DIFF COLLECTIVE)
YAW (LAT DIFF CYCLIC)
STICK FORE & AFT (LONG DIFF COLLECTIVE)
CONTROL ANGLE
60 Vh 80 M.P.H

Fig. 9.

W.11 control characteristics at constant torque. $\frac{3}{4}$ max. torque = 28,875 ft. lb.

transmitted to the spider by a quick thread mechanism concentric with the rotor hub; and a tilting movement about a fixed axis. This tilting motion is actuated by a second sprocket, concentric with, and situated above, the first sprocket, the rotation of which is converted into spider tilt by means of a "Z" crank mechanism.

The hub control mechanism terminates in the actuating sprockets of which the lower, causing axial displacement of the hub control spider, varies the collective pitch of the blades and the upper, by tilting the hub control spider, imposes upon the blades a cyclic pitch variation of fixed azimuth.

Each collective pitch sprocket of a rotor is connected through a cable transmission to one extremity of a stationary spider in the fuselage and each of the cyclic pitch sprockets is actuated through a similar transmission by the displacement of the extremities of another stationary spider. The two stationary spiders are the heart of the "control exchange" mechanism, and are shown in Fig. 8 in diagrammatic form. Axial and tilting movements of the "exchange spiders" combine to control the actuating sprockets in the hubs. The pilot's control organs are linked with the "exchange" spiders so as to produce the correct combinations of common and differential increments of collective and cyclic pitch.

This linkage is assisted by "Servodyne" hydraulic jacks controlled by follow-up valves mounted on the jack cylinders and moving with them. Hydraulic pressure is supplied by two pumps driven by the engine and rotor system respectively which maintain two air-loaded accumulators under pressure. In case of hydraulic failure, a cut-out lever in the cockpit establishes communication between the pressure and bleeder parts of the system, releases the jacks and a purely mechanical linkage is maintained (with a small lost motion in the follow-up valve).

The terms "common" and "differential" are used for inter-rotor relations and the terms "collective" and "cyclic" retain their usual connotation of inter-blade relations in each rotor. The distinction is arbitrary, but useful if applied consistently, because the terms have to serve in combinations such as "common collective pitch control" describing the simultaneous and equal variation of pitch of all the blades of the machine.

Basic control functions, therefore, consist of the following. Raising and lowering the "collective exchange" spider by means of the pitch lever produces common collective pitch change. The pilot's control column communicates tilting motion about the pitching and/or rolling axes to the "collective exchange" spider, which causes differential variation of collective pitch (and lift) between the rotors.

Finally, the rudder pedals impose a tilting motion on the "cyclic exchange" spider about its rolling axis, which causes the tip path planes of the two rear rotors to be differentially tilted in the fore and aft sense, thereby producing a couple between the opposing horizontal thrust components.

4. DEVELOPMENT OF CONTROLS

With controls connected as described so far, the machine is fully controllable, but to extend its range of forward speeds and to improve its flying qualities further control connections are being gradually introduced which are listed in order of importance.

(*a*) In forward flight at any appreciable speed it becomes essential to reduce or suppress the flapping of the blades. To this end all rotors must receive cyclic pitch control in the same sense and roughly of equal magnitude. This is done by imposing an axial displacement

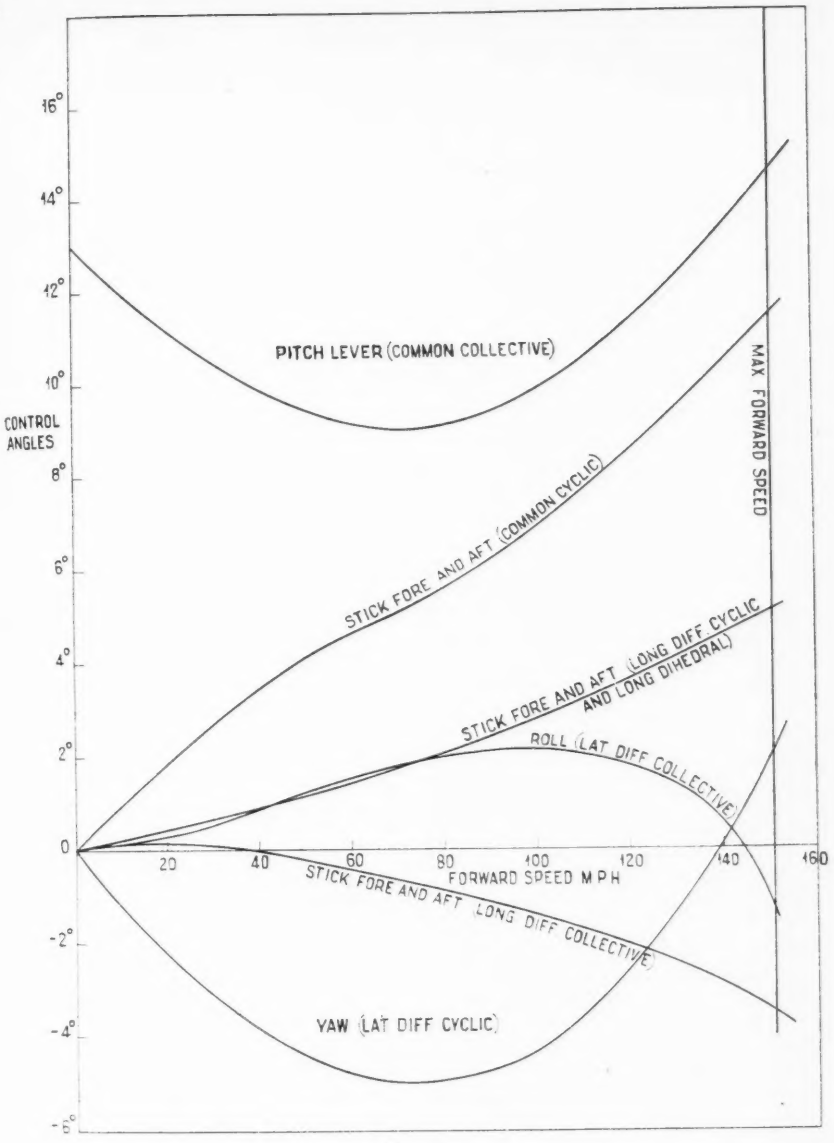

Fig. 10.
"Air Horse" level flight control characteristics.

on the "cyclic exchange" spider whenever fore and aft movement of the control column takes place. The interlinkage is adjusted for suppression of flapping in level flight (Fig. 10). Nearly complete suppression of flapping is practicable by means of a linear interlinkage. Such an interlinkage is made possible by a definite relation between stick position and forward speed, such that

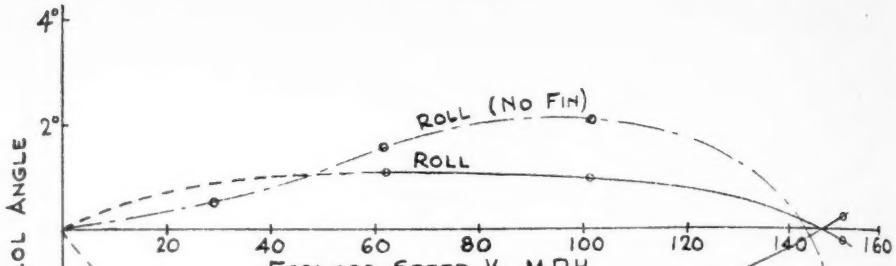

Fig. 11.
W.11 level flight control characteristics. Fin controlled by rudder bar. Fin angle = 2 × diff. cyclic pitch angle.

the stick is maintained in a position further forward for increased speed. Reference will be made below to this feature, which is related to the dihedral between the rotors.

(*b*) Initially the orientable fins are under control of a trimmer wheel operated by the pilot. Subsequently the fins will be positively inter-linked with the rudder pedals. This feature will reduce the interference between yawing and rolling controls and consequently the required trim in roll when flying forward. Fig. 11 illustrates the effectiveness of this method, which is explained in greater detail below.

(*c*) The stability characteristics of a three-rotor helicopter are greatly influenced by the amount of dihedral between the rotor discs. Effective dihedral is determined not by the mechanical axes, but by the virtual axes, normal to the plane referred to where no cyclic pitch change takes place. It has been found that negative dihedral contributes to dynamic stability in hovering while stick-fixed stability in forward flight requires positive dihedral. This conflict can be resolved through the introduction of variable dihedral by means of a gradual fore and aft tilt of the cyclic "exchange" spider, thereby producing virtual differential tilt between the front rotor, on the one hand, and the two rear rotors on the other. Dihedral variation will also be inter-linked with fore and aft movement of the control column (Fig. 10).

(*d*) It is intended to provide an inter-linkage between the common pitch lever and the directional controls, so as to ensure yawing equilibrium throughout the range of rotor r.p.m. in flight (Fig. 12).

Although most of the specific features of the Air Horse are based on well-known principles, the number of possible combinations is large and the selected combination has been evolved through a long process of elimination.

II. CLAIMS AND CRITICISMS

1. CONTROL AND STABILITY

(*a*) The control of the aircraft in roll and pitch is extremely powerful in the sense that only a fraction of available control range is required to obtain angular accelerations above those common in present-day helicopters. Furthermore, control couples are nearly "pure" and not associated with horizontal forces until the aircraft has actually changed its attitude in response to the application of control. Both features are

caused by the fundamental method of multi-point control and cannot be equalled in a single-rotor helicopter. From another aspect these features are the basis for almost complete suppression of flapping in forward flight.

(*b*) In a single-rotor helicopter, directly controlled by actual or virtual tilt of rotor disc (and thrust), the effectiveness of control depends upon the magnitude of that thrust. Under conditions of accelerated flight rotor thrust may increase and, what is worse, may also decrease to vanishing point or become negative. There is the danger therefore of loss of control or even reversal of control. In the three-rotor machine the basic control functions of pitching and rolling are produced by increments of lift and not by the lift itself. An increment of lift can always be obtained by blade pitch variation, even when the lift itself is going through zero. It can be said that basic control functions are operative in three-rotor machines under all conditions of flight, without exception.

(*c*) Every flying machine with less than six totally independent means for producing forces and moments to cover the six degrees of freedom of a body in space, must have some measure of interference between the available controls. We must, however, distinguish between direct and indirect interference. Direct interference means that, in imposing the desired forces or couples on the machine, we produce *simultaneously* undesirable forces and/or couples in other directions. Indirect interference means that a secondary force or couple arises from the change in the condition of flight brought about by the application of control. Indirect interference, unless excessive, is scarcely noticed by an experienced pilot because of the intervening delay due to

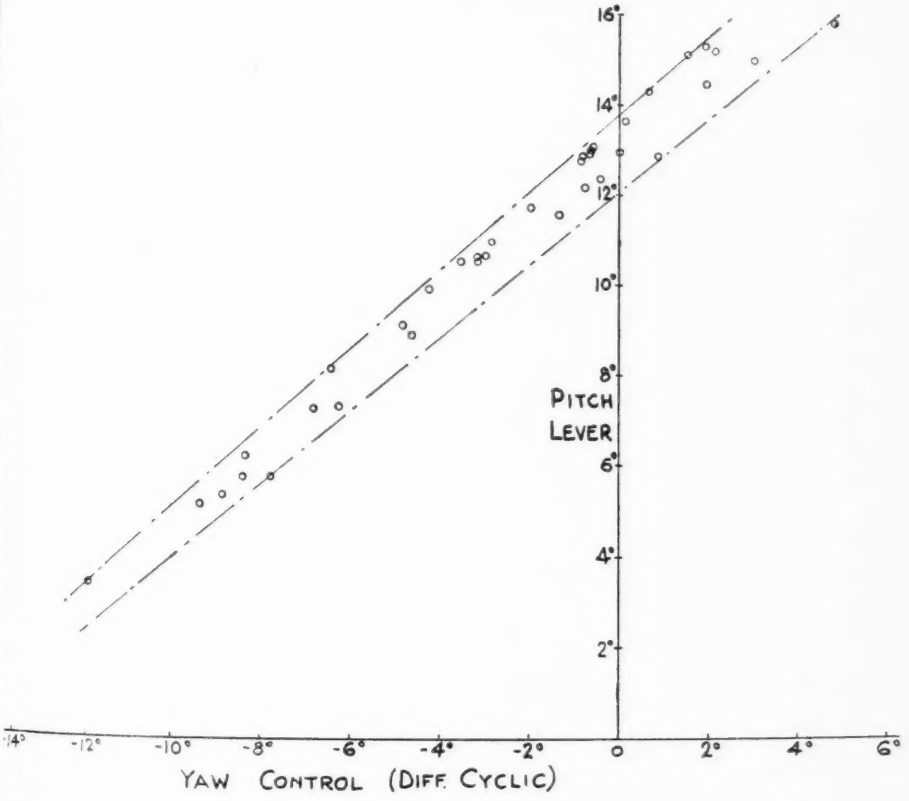

Fig. 12.
W.11 relation between pitch lever and yaw control.

the inertia of the aircraft. It is felt by the pilot as a need for a change in trim.

The control system chosen for the Air Horse is subject to two types of undesirable direct control interference. The yawing equilibrium of the machine is disturbed whenever common collective pitch is applied. The required correction is shown in Fig. 12 and will eventually be done mechanically by means of the " datum " inter-linkage already mentioned.

Another type of direct interference is the disturbance of equilibrium in roll when yawing control is applied *in the presence of forward speed*. This is due to the differential change of virtual disc incidence against the flight path between the two rear rotors as a consequence of differential application of cyclic pitch. Change of virtual disc incidence causes a change in lift roughly proportional to the flight path speed, as well as a change in horizontal thrust component which is the primary purpose of cyclic pitch application. Thus the previously balanced lifts of the two rear rotors become unbalanced and a rolling couple is set up which has to be corrected by displacement of the control column in the rolling sense. Stick displacement in roll to trim the aircraft in steady level flight is required, owing to the operation of yawing control which accompanies the variation of collective pitch. This amount of trim in roll is shown in Fig. 10.

When the orientable fins are positively interlinked with the rudder pedals yawing moments are partly obtained from fin lift in forward flight. This fact reduces the required differential change in disc incidence and hence the resulting unbalance of rolling equilibrium. Fig. 11 illustrates the effect of this feature on the required trim in yaw and roll in steady forward flight.

In future machines the introduction of cyclic pitch change in the lateral sense as well as the fore and aft sense is being considered; both to be independently controlled, and only the lateral cyclic pitch control to be connected to the rudder pedals. Thus fore and aft cyclic pitch control will only be used for the suppression of flapping in forward flight and lateral cyclic pitch control will be used solely for producing yawing couples. In this way disc incidence will not be varied in the flight direction and no disturbance of the rolling equilibrium will occur.

The pull-out which can be defined as an increase of lift accompanying the operation of pitching control, is an example of direct control interference which is accepted as natural and desirable.

The above exhausts the main cases of unavoidable interference, but it is the absence of the numerous other possibilities of interference which constitutes an outstanding claim of this configuration.

(*d*) In most flapping rotors the azimuth of maximum flapping angle is not in phase with the flight path. This fact is a source of an indirect control interference and it has been realised recently that in single-rotor machines, in some manœuvres, this interference can be troublesome. In three-rotor machines the contribution of lateral components of flapping to the rolling equilibrium of the machine is negligible.

(*e*) In fixed-wing aircraft the conception of static stability has changed within the past decade from denoting the sign and magnitude of the derivative of pitching moment, with respect to aircraft attitude in a succession of steady states at constant forward speed, to the present conception of stick-fixed stability describing the relative positions of the control column with change of forward speed. The two conceptions, although not identical, are related and cannot differ widely in a conventional layout. Stick-fixed stability can be taken as representative, being the more practical magnitude.

The direct significance of these concepts in helicopters is as yet uncertain but, in this respect, a three-rotor (or tandem) helicopter

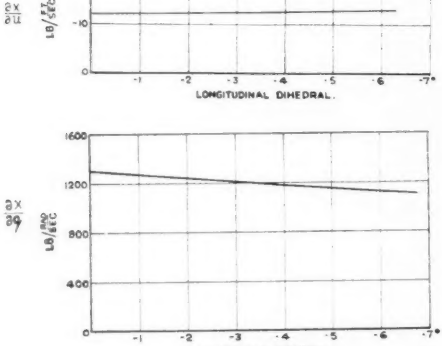

Fig. 13.

Longitudinal stability in hovering flight at sea-level. (C.G. position 59 per cent. aft of front rotor.)

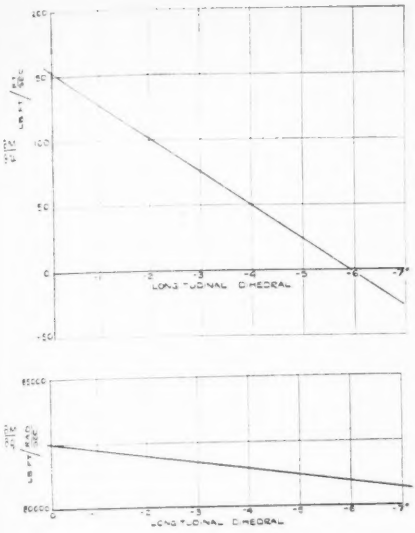

Fig. 14.

Longitudinal stability in hovering flight at sea-level. (C.G. position 59 per cent. aft of front rotor.)

is more similar to the fixed-wing aircraft than to the single-rotor helicopter. Static stability in the original sense is influenced by the horizontal position of centre of gravity relative to the geometric centre of the lifting surfaces, although the vertical CG distance has a great de-stabilising influence in a helicopter but not in fixed-wing aircraft.

There is one fundamental difference between the Air Horse and a fixed-wing aircraft. The stick-fixed stability in the three-rotor helicopter depends almost entirely on the longitudinal dihedral between the front rotor and the rear rotor pair. The two "stabilities," therefore, are entirely independent. In the Air Horse both are positive *throughout the speed range.*

$\delta M/\delta\alpha$ is made negative (conventionally denoting positive stability) by placing the centre of gravity forward of the geometric centre of the rotors by 8 per cent. of the distance between the front rotor and the line joining the rear rotors. This amount covers the de-stabilising influence of interference between front and rear rotors in forward flight, as well as the de-stabilising effect of the vertical distance between the CG of the aircraft and the plane of the rotors, the latter being approximately three times as severe as the former. It is assumed that the instability of the fuselage body is fully balanced by its own tailplane. No other form of helicopter shows any promise of attaining negative $\delta M/\delta\alpha$ over the whole speed range. Usually an unstable region exists at low speed.

Stick-fixed stability is achieved by positive dihedral (or variable dihedral becoming positive in the upper range of forward speed). This stability is illustrated in Fig. 9, giving the position of controls over the speed range at constant torque, as well as Fig. 10 showing these positions in level flight.

(*f*) Dynamic stability has been investigated mainly in hovering. It is well known to-day that dynamic instability in hovering is mainly caused by the existence of a moment derivative with regard to horizontal translational motion. In a three-rotor machine having a (virtual) negative dihedral, this derivative can be suppressed and even changed in sign both longitudinally and laterally. Under such conditions dynamic stability is obtained as shown in Figs. 13, 14 and 15, representing graphs of force and moment derivatives, and the stability parameters over the dihedral angle. The graphs refer to longitudinal motion, but apply to lateral motion as well. I am

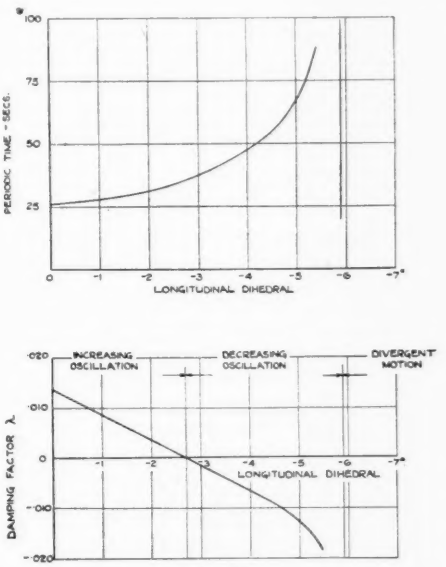

Fig. 15.

Longitudinal stability in hovering flight at sea-level. (C.G. position 59 per cent. aft of front rotor.)

indebted for these graphs to Dr. Sissingh who very kindly confirmed and improved upon our calculations.

2. VIBRATIONS

(*g*) Vibration phenomena in a three-rotor machine can be even more complex than those in a single-rotor machine, but multi-rotor machines like multi-cylinder engines offer an opportunity for balancing out of many of the periodic impulses inseparable from rotor operation. It is obvious that removing the source of vibration from the position of the occupants reduces the effect of such vibrations on passengers and crew.

3. UNDERCARRIAGE

(*h*) Because of the geometry of the three-rotor helicopter, the undercarriage can be provided with relatively large track and wheelbase without any weight penalty. The importance of this feature will be apparent when it is recalled that the majority of accidents to rotating wing aircraft in the past have been caused by overturning on the ground and could have been avoided by increasing the track of the undercarriage. In the Air Horse the legs are so spaced that non-symmetrical landings are hardly more severe than symmetrical landings.

(*i*) The undercarriage is organically built into the outrigger structure, so it is comparatively easy to provide undercarriage legs with long travel to absorb the energy of high rates of descent, the advantages of which will be discussed later.

4. LAYOUT

(*j*) The layout of the machine provides unobstructed entry into the main load compartment.

(*k*) As can be seen from the layout the engine compartment is easily accessible, which facilitates the tasks of servicing the engine and its accessories as well as the gearbox and the control exchange unit.

(*l*) On single-rotor machines, the fore and aft limits of centre of gravity are rigidly prescribed, not so much from the point of view of static stability (which, in any case, is problematical and depends mainly on the vertical position of CG) but in order to maintain full control range. In the Air Horse, because of the extremely powerful pitching control, such a restriction does not apply in practice and no difficulty will be experienced in flying with the centre of gravity as far as two feet off the mean position in either direction. This fact greatly facilitates the loading procedure and is likely to be especially appreciated in freight-carrying machines.

(*m*) Because of the high elevation of the main rotors and the absence of a tail rotor, the Air Horse is completely free from the hazards to personnel on the ground possible with single rotor, as well as fixed-wing machines.

(*n*) The triangular layout of the rotor system is responsible for the fact that the height at which the ground cushion is effective exceeds the individual rotor diameter. This effect is absent in twin-rotor machines.

5. CRITICISMS

It is natural to question the complexity of a three-rotor machine with its multiplication of blade articulations, transmission elements and controls. Furthermore, it is expected that the weight penalty, as well as the drag penalty of the outriggers and long travel undercarriage legs, will have to be justified on performance grounds, in spite of the numerous advantages of the configuration.

6. PRINCIPLES OF EVALUATION

No answer to such criticisms can be provided without first choosing a suitable criterion derived from a distinct approach to helicopter operation. It is my intention in this paper to underline the quantitative approach and to choose the point of view of the commercial operator selling the use of helicopter communication. In this way, from the great number and variety of considerations applicable to the evaluation of a helicopter, those expressible in economic terms can be selected and correlated under the guidance of the over-riding aim, "to provide helicopter transport services at low cost in terms of pence per ton mile or passenger mile at a speed leaving a substantial margin compared with ground transport and accompanied by the highest possible safety."

Considerable experience is required to apply this guiding principle to helicopters with any certainty and it is too early to expect general agreement on the estimates and methods used in this paper, but I believe

that even poor quantitative data are better than none. Numerical work has convinced us that in the economic field broad conclusions derived from aircraft data are not critically dependent on their accuracy. In short, *unity of conception* is more important for bringing order into a maze of variables than accuracy of assumptions.

Although transport operation is here considered as the basic task of the helicopter, other types of operation can also be expressed in quantitative terms. The main alternative group of duties for helicopters can be summarised as "crane operation," their purpose being the lifting and manipulation of weights from restricted areas with little or no haulage. The important application to crop spraying belongs to this category. The choice of transport operation for the basic evaluation of the Air Horse expresses my faith in the potentialities of this field of operation, which I believe to outweigh all others in the long run.

The evaluation of helicopters from the point of view of private flying is different in many respects and often leads to conclusions opposite to those applying to commercial operation. For commercial operation large payloads are wanted and the largest possible machines to carry them. For private flying it is essential to carry a fixed payload and to endeavour to design the smallest possible machine to do it. When the designer learns to improve the percentage of useful load by x per cent. he will reduce the unit *cost* of commercial helicopter transport roughly by x per cent. He will, however, reduce the *size* of a machine destined for private flying, usually by more than x per cent. It is understandable why the Cierva Autogiro Company has simultaneously built the largest and smallest practical helicopters under development.

Once commercial operation is considered, the criticism of complication loses its significance as an independent yard-stick in evaluating the helicopter or any other piece of equipment. From this point of view, to be significant, complication must be expressible in terms of first cost and/or maintenance.

It is believed that the multiplication of components carries with it the tendency to cheapen manufacture by increasing numbers. We are all aware of numerous examples in engineering where multiplication of components has no specific effect on first cost. I only need to mention multi-cylinder engines or ball-bearings.

Final judgment on maintenance will have to await practical experience, but it is believed that the advantage of accessibility obtainable in a three-rotor machine of the size of the Air Horse and the reduction in the relative cost of spares through interchangeability, outweigh the disadvantages of multiplication.

The evaluation of the three-rotor configuration from the point of view of performance expressed in terms of transport economics will be divided into two main chapters dealing with the relatively independent features of three-rotor configuration and long travel undercarriage.

III. ECONOMICS OF THREE-ROTOR CONFIGURATION

1. INTRODUCTION

Are the advantages of the three-rotor helicopter accompanied by a weight and drag penalty, leading to increased cost of helicopter transport?

In this paper we are mainly concerned with examining the three-rotor configuration in comparison with others, but other things must be equal. Among other things we include the remaining principal factors determining the economics of helicopters. These factors are classified under four headings:—

Size
Configuration
Choice of parameters
Detail design.

Obviously we cannot replace a theoretical evaluation, however uncertain and based on inspired guessing, by a direct comparison of existing types simply because no such types are available of equal size, equal approach to optimum parameters, or equal stage of design development.

Therefore, it was necessary to develop methods of comparison which establish the effect of all the relevant factors on the "economic efficiency" of the helicopter. Details of the method are given in the appendix and it is claimed that both the approach and the numerical values of constants chosen are a better representation of design practice than other methods so far published. At the same time, I know that

every method in this field relies on bold generalisations and provides a "broad basis for disagreement."

Referring to the chosen criterion of economic efficiency, we can narrow it down by first examining the conditions of safety and speed. Some of the advantages of the three-rotor configuration enumerated above are concerned with safety. There can be no doubt that powerful and unfailing control, static and dynamic stability, broad undercarriage base, and high energy absorption, combine to make the Air Horse one of the safest helicopters under development. Furthermore, the relatively favourable percentage of useful load achieved has not been bought at a sacrifice of load factors or relaxation of fire, or other precautions.

The next big step towards safety is the provision of two engines. This will be done in the next three-rotor helicopter now in the design stage, which will be powered by two Merlin engines. For passenger transport duties, which we are primarily considering here, especially when crossings of water stretches are included, it is essential to have a twin-engined power plant. In fact, it is thought likely that, except for special duties, the twin-engined version will be the only one employed for civil transport. Investigations of economic efficiency therefore have been applied mainly to the twin-engined machine.

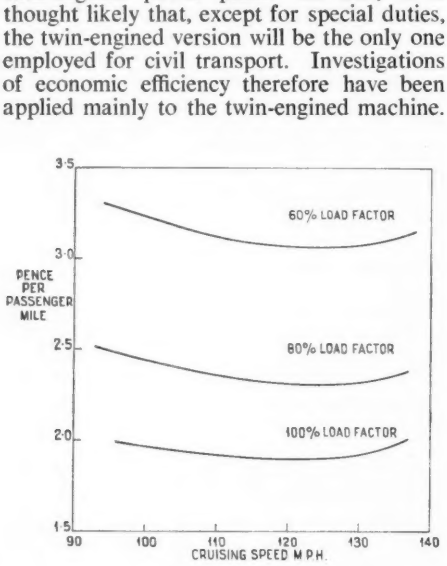

Fig. 16.

Air Horse passenger carrier direct flying costs. Effect of cruising speed.
All-up weight = 17,500 lb.
Stage length = 100 miles
Utilisation = 2,400 hrs./year

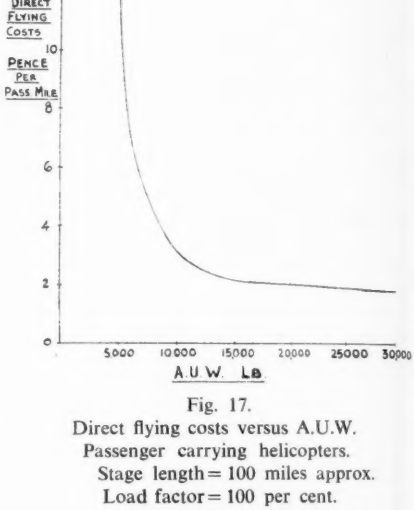

Fig. 17.

Direct flying costs versus A.U.W.
Passenger carrying helicopters.
Stage length = 100 miles approx.
Load factor = 100 per cent.
Utilisation = 2,400 hrs./year

Further advances in safety are possible by application of certain automatic controls. I would single out for attention automatic limitation of rotor r.p.m. and automatic conversion to auto-rotation. These items, as well as other features of automatic control, belong to our programme of development but cannot be counted on at present. Experience teaches us to proceed with caution with all automatic devices before any claim can be made of truly improved safety.

Similar comments apply to de-icing, which is also on our agenda of flight development.

Finally, navigational and flight equipment are of the greatest importance, but do not, as such, belong to the constructor's field of activity.

Several considerations tend to eliminate speed as a variable at the present stage. The words "substantial margin compared with surface transport" have been chosen deliberately to convey the belief that the value of speed increases in large steps and not gradually. The economic value of speed to the customer cannot be simply expressed in monetary terms, being too closely connected with our daily habits. Furthermore, time-

table loss is too important a factor to be left out if any attempt is made to put a price on speed. Thus, the reduction of travelling time for a journey from London to the Midlands from 2½ hours to 50 minutes allows a full day's work to be done at the destination. A further reduction to 25 minutes is of little consequence. Similarly 10 minutes difference because of wind fluctuations is easily bearable on such a journey.

Moreover, all helicopters under development to-day are inherently capable of substantially identical cruising speeds of about 115 m.p.h. and the Air Horse promises to attain this speed with economical cruising power. It can be seen from Fig. 16 that 10 m.p.h. either way about this cruising speed has only a small influence on direct cost of transport, but in view of wind fluctuations a cruising air speed of 110 m.p.h. appears a minimum for passenger transport operation.

We conclude from the foregoing that speed can be eliminated as a factor in comparing the economic efficiency of helicopters and are left, therefore, with a cost comparison alone

While true economic efficiency must finally be judged by the cost of helicopter transport to the consumer, it will be appreciated that evaluation of equipment has to be limited to what has come to be known as direct cost and includes only costs associated with the use of the machines, but does not include the cost of ground installations or general administration, nor those incurred in selling the service to the customer. This basis is entirely satisfactory for comparing helicopters, but may be highly misleading in comparing helicopters and fixed-wing aircraft costs, since one of the prime advantages of the helicopter is the enormous reduction in ground installations.

In what follows no attempt has been made to present fully up-to-date figures. Results shown represent different levels of approximation, but the philosophy underlying these calculations is consistent and at this stage little is gained by attempted precision. No avoidable approximations have been used on the aerodynamic side and the design experience of our Company, as well as published data on other helicopters, have been included.

2. EFFECT OF SIZE

Figure 17 illustrates the fact that up to the size of the Air Horse and beyond, the effect of size on cost is predominant. This graph is based on existing helicopters, but includes the twin-engined Air Horse. Fig. 18, applied to three-rotor machines only, shows that size has a far less pronounced effect on the percentage of disposable load. Such a conclusion is roughly in accord with fixed-wing experience in the range of sizes considered here and represents the balance of several opposing tendencies. The effect of size on the cost of transport is due to cost items, such as crew remuneration, which are predominant in small sizes.

These illustrations are intended to underline the importance of size. This importance is so great that all evaluation must remain theoretical so long as comparison of equal size machines cannot be made in practice. The effect of size on economic efficiency is not confined to any one configuration, but our Company, which set out to increase the size of helicopters, found that multiplication of rotors was the only means of doing so without adopting new and untried principles to surmount the problem of increasing rotor sizes.

It will be noticed that Fig. 20 is plotted over engine power rather than all-up weight.

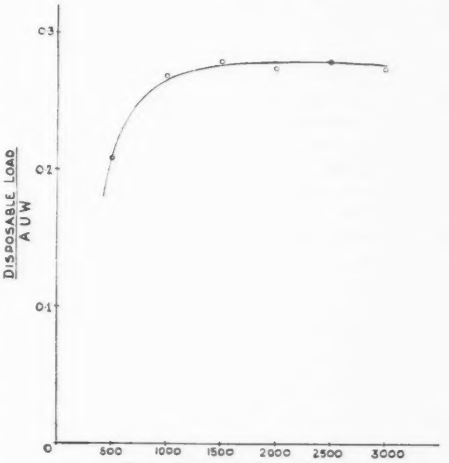

Fig. 18.

Disposable load/A.U.W. versus power at rated altitude.

3 rotor helicopter, tapered, twisted blades. Tip speed = 550 ft./sec.

Optimum disc loading. Minimum solidity. Minimum undercarriage travel.

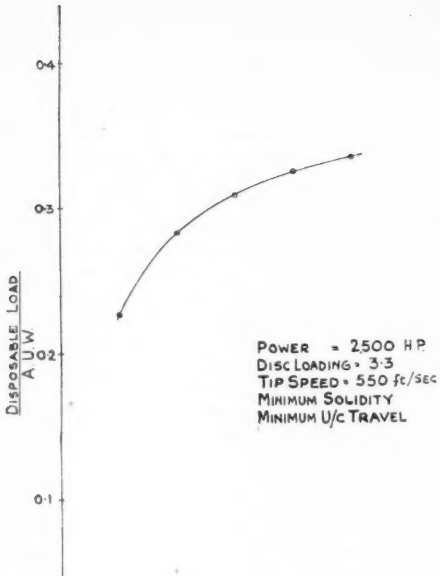

Fig. 19.
Disposable load/A.U.W. versus number of rotors.

I need not say much to convince those with any experience in aircraft design that this is the only way of representing realities of design procedure. In practice we choose an available engine or engines; all-up weight remains a variable until disc loading is chosen. Of this more will be said later.

3. EFFECT OF CONFIGURATION

Having found that valid comparisons can only be made between helicopters of equal size, we now face the greatest difficulty when dealing with the core of our argument, namely, the effect of configuration on cost of transport.

First, we shall admit that comparisons of configurations based on totally different conceptions are built on a slender foundation until such machines have not only actually flown, but have been developed to C.O.A. standard and carry full equipment.

Second, we shall simplify the problem somewhat by concentrating in what follows on "percentage disposal load." For machines of equal size this criterion almost entirely determines cost per ton mile when the operating factors of speed, utilisation, and load are assumed to be constant and so long as first cost, as well as maintenance allowance, must be dealt with on the basis of general estimates and not specific experience.

It is more profitable to restrict our approach and to compare multi-rotor helicopters having different numbers of rotors. In this limited field, at least, the comparison expresses real trends. Such an evaluation extends to all outrigger machines, from side-by-side twin rotors to three- and four-rotor configurations. It is based on the assumed laws by which weights of different components alter with basic physical magnitudes of the helicopter to which we shall return later. Fig. 19 shows that a considerable improvement results from increasing the number of rotors from two to three. Further possible improvement is limited and may no longer justify the additional complication.

This graph cannot, of course, cover single rotor, tandem, inter-meshed, or co-axial configurations, which are the present practical competitors of outrigger layouts. In each case, if we take the side-by-side outrigger system as a basis, there will be items causing weight reduction as well as items causing weight increase. My point is that the best alternative system, which I believe to be the tandem machine, is only marginally better than the side-by-side twin and therefore probably inferior to the three-rotor machine.

Starting off with a superficial impression that the weight embodied in the outriggers is sacrificed for the safety features of the three-rotor configuration, we now see that this configuration actually promises to be more economical in weight and, at worst, cuts even with the best alternative.

Other performance aspects are more easily dealt with. It can be stated with some assurance that the gliding angle of the three-rotor machine as a whole is of the same order as that of the best existing single-rotor machines. This is due partly to the utilisation of the rear outrigger booms to produce lift in forward flight and partly to the effect of size. Further, the percentage of lift lost because of vertical drag of the slipstream in hovering is no greater than in existing single-rotor machines.

Aerodynamic interference between rotors in forward flight, which affects stability

characteristics, has been tested and found to be negligible for the Air Horse configuration. Interference in hovering, which determines the aerodynamic lifting efficiency and thereby the all-up weight and percentage disposable load, is also small and must await accurate measurements for reliable results.

4. EFFECT OF DESIGN PARAMETERS

The third main factor which determines weight efficiency and thereby cost of transport, is termed "choice of parameters." It is here that investigations of weight economy are most fruitful, even essential. This subject belongs to the theme of the paper in the sense that comparison between configurations is only valid when the designer has made the best of each by correct choice of parameters. Although finding the optimum is difficult, it is easy to demonstrate how a bad choice of parameters can wreck a good configuration.

In outline, our approach consists of the following steps, each containing somewhat bold and debatable assumptions, which, in combination, are plausible and consistent.

1. Definition of permissible all-up weight.
2. Determination of truly independent parameters.
3. Subdivision of component weights into groups depending on individual parameters and their combinations.

Briefly, all-up weight is limited to that which can be lifted vertically at a rate of 6 ft./sec. by maximum engine power without wind or ground interference under the worst atmospheric conditions in which the machine is expected to operate. To avoid a "multiplication of pessimism," average individual efficiencies are chosen and a total allowance of 4 per cent. power loss is made to cover all errors.

There are four major design parameters, once the configuration is settled and the power unit chosen:—

(*a*) Disc loading
(*b*) Tip speed
(*c*) Blade solidity
(*d*) Undercarriage stroke.

Of these some prove on investigation to be dependent upon others.

Truly independent parameters are only disc loading and tip speed. The latter is representative and the nominal tip speed corresponds to maximum engine r.p.m. Extensive investigations have led to the elimination of rotor solidity as an independent parameter. Such investigations have shown that solidity should always be chosen so that blade tip stalling is prevented under the worst conditions of forward flight and that this solidity is always in excess of optimum solidity in hovering. Hence the practical optimum of solidity is determined by disc loading and tip speed. Undercarriage stroke is settled by general reasoning in a manner mentioned below.

Component weights are first subdivided into categories depending upon physical magnitudes: power, all-up weight, rotor diameter, torque, ground reaction, centrifugal force and their combinations and, since each of these can be expressed in terms of the two independent parameters, groups finally emerge which depend upon a specific combination of the independent parameters. Equally, all-up weight depends upon the same parameters.

Figures 20 and 21 illustrate the effect of disc loading on the percentage of disposable load for a given power. It is seen that the effect of disc loading flattens out and remains stationary over a considerable region. Disc loadings of the two Air Horse types are near the maximum. I would like to make it clear that these graphs represent a comprehensive approach. In all cases, for example, solidity is automatically adjusted to avoid tip stall and undercarriage stroke is automatically increased to absorb the energy of unaided vertical descent without power.

The moral from the disc loading graph is that in a certain region the effect of disc loading is predominant, but an equally important conclusion is obscured by our replacement of the cost of transport criterion by the more convenient disposable load criterion. Low disc loading means low forward speed on grounds of power limitation until at disc loadings around three, power no longer limits forward speed at the present state of the art. Low speed increases cost of transport and by exceeding the threshold of "substantial margin," may even make the helicopter entirely unsuitable for transport operation. On the other hand, for "crane" operation, disposable load for a given power is all that matters.

If we had a graph of a single rotor machine to compare, we would find the percentage of disposable load going steadily up with decreasing disc loading and hence a conflict

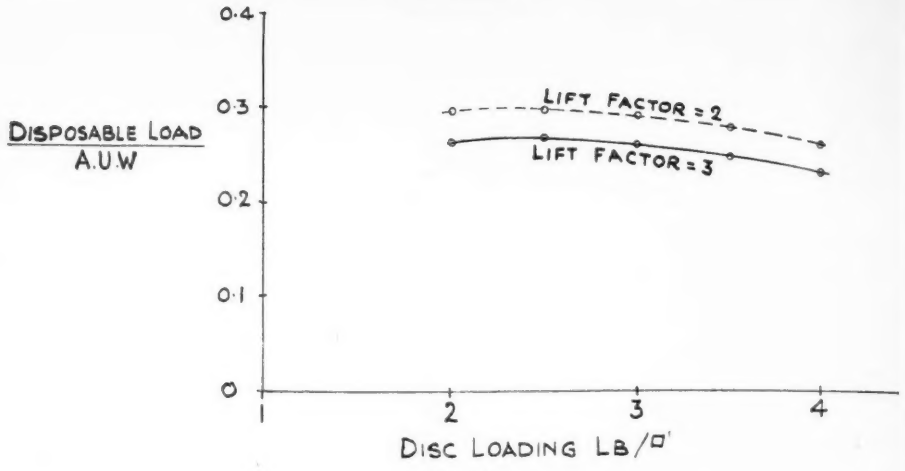

Fig. 20.

Variation of disposable load/all-up weight with disc loading.
Engine power = 1,000 h.p. Minimum solidity.
Tip speed = 550 ft./sec. Minimum U/c. travel.

between the "crane" and "transport" requirements. In the three-rotor configuration, on the other hand, both types of operation call for fairly high disc loading. We have laid it down before that two helicopters can only be legitimately compared when of equal size and when both represent the optimum combination of parameters of their type. Now we find that the optimum disc loading single-rotor machine may be a practical impossibility on account of low forward speed and the consequent limitation to one type of duty only. Such a limitation of the market of any one machine may be an unbearable financial burden.

The disc loading influences the limit lift load factor by virtue of the fact that every rotor has an absolute maximum of lift. If the lift factor is related to the absolute maximum of lift then it is inversely proportional to disc loading. If, on the other hand, the lift factor is arbitrarily fixed by airworthiness requirements, it remains constant, whatever the disc loading. The difference between the two assumptions has an effect on optimum disc loading, as illustrated by the two curves on the graph.

In contrast to disc loading graphs, those showing percentage of disposable load over representative tip speed (Fig. 24) have no optimum. We have to re-emphasise that rotor solidity is adjusted for each tip speed to a value determined by tip stall in forward flight. Further, these graphs are highly sensitive to the profile and quality of the blades and assumptions have to be made relating engine r.p.m. of maximum power, hovering and cruising flight. If these are examined in detail it will be seen that much could be gained if a two-speed reduction gear between engine and rotor system were available. This possibility has been disregarded.

We learn from these graphs that high tip speed is beneficial, but no account has been taken of compressibility, for which available data are insufficient. In any case, experience goes to show that increases in tip speed must be undertaken with caution and the benefit of tip speed beyond 550 f.p.s. is not large.

The figure includes a graph of the kinetic energy of the rotors. It is seen that the effect of decreasing solidity nearly offsets that of increasing tip speed and the kinetic energy increases only very slightly, with increasing tip speed. The only way to increase kinetic energy substantially is to introduce more weight into the blades than the minimum required, calling for an increase of other components which depend on centrifugal force. It is better to increase the weight without increasing solidity, because in the latter case not only is weight added but hovering efficiency is also reduced, due to

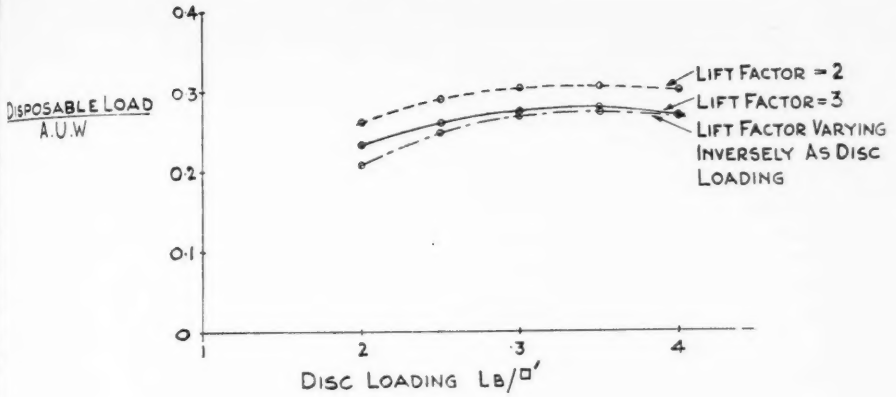

Fig. 21.

Variation of disposable load/all-up weight with disc loading.
Engine power = 2,500 h.p. Minimum solidity.
Tip speed = 550 ft./sec. Minimum U/c. travel.

working further away from optimum blade loading and hence blade incidence.

The graphs are based on blades of the highest quality obtainable in practice. More conventional blades will show less improvement with high tip speed.

5. DETAIL DESIGN

Finally, we have to consider the standard of detail design. Machines identical in power, configuration, and having the same principal parameters can have very different economic efficiencies, depending upon the standard of detail design. This standard will determine disposable load, fuel economy, maintenance, and depreciation.

The standard of design depends mainly on the skill of the designer and his team and on the stage of development of the type. Other contributors to this discussion have dealt more fully with this aspect based on a helicopter in a more advanced stage of type development.

A novel configuration presents new problems requiring time and experience for their solution. It calls for caution in application, but it also offers new opportunities to the designer. In particular, larger size contributes to the possibility of greater refinement and the layout of the Air Horse facilitates attention to ease of maintenance. The threefold repetition of many components makes every improvement in the design of such components three times more effective.

Many details can be analysed for an optimum combination of parameters in the same way as the complete aircraft. In such cases it is essential to formulate effective criteria which embrace all the important aspects of the problem. Examples are the analysis of the cooling system, where power and weight have to be balanced; the design of fairings, where weight and forward drag have to be compared; similarly, the choice of outrigger booms, the diameter of transmission shafts and undercarriage legs.

The cooling system has the advantage of being amenable to a full evaluation from scratch, on the basis of unit data and in the Air Horse the cooling system weight is of the order of 0.25 lb./take-off h.p. (including variable pitch fan) and cooling power is $1\frac{1}{4}$ per cent. of engine h.p.

On the other hand, the undercarriage legs of novel conception had to be completely designed before an analysis of optimum parameters could be made. Better choice of ruling dimensions by itself will save some 20 per cent. of the weight of this component.

Such weight saving by co-ordination is the most fruitful and least expensive of all, but further savings are possible when an increase in manufacturing costs can be faced.

Much experience is required to decide where refinement of design has to stop on

account of cost, but some quantitative guidance is obtained from transport cost analysis. The value of weight in a helicopter is greater than in fixed-wing machines. On the basis of 2,400 hours annual utilisation (being the principal variable in this connection) one lb. of weight in the Air Horse is worth £25 in selling price. It is fairly obvious that the best investment for weight saving can be made in the cheapest components. It is common to all types of efficiency that it is best secured by "equality of sacrifice," whether it is uniform slipstream, or uniform cost of components per lb. weight.

Apart from cost of manufacture, the cost of design cannot be neglected. This introduces the management of theoretical and experimental research. I am tempted at this point to digress into a general reflection upon the part played by science and art in design. There is a story about the great American physicist, Willard Gibbs, who was reputed to have refrained from all public speaking. The only exception was reported from a convention of "educationists" where the question was debated whether mathematics or languages were better subjects at school. Willard Gibbs rose to pronounce the only speech he ever made in public, saying, "Ladies and Gentlemen. Mathematics *is* a language." May I be permitted to follow in his footsteps when confronted with the question whether helicopter design is a science or an art and simply repeat that, when applied to design, science *is* an art.

It would appear that the Air Horse constitutes an important advance in economic efficiency on account of its size, made possible by multiplication of rotors; that the three-rotor configuration compares favourably with the best known alternatives and its numerous advantages are not bought at a sacrifice in economics; that the Air Horse represents a choice of design parameters approaching the optimum in all but tip speed, and that, for its potentialities to be fully applied in detail design, type development will be pursued, promising to reach really high standards in the twin-engined version.

4. ECONOMICS OF LONG TRAVEL UNDERCARRIAGE

We now come to the evaluation of the long travel undercarriage peculiar to the Air Horse. This feature is facilitated by the three-rotor configuration, but does not necessarily follow from it.

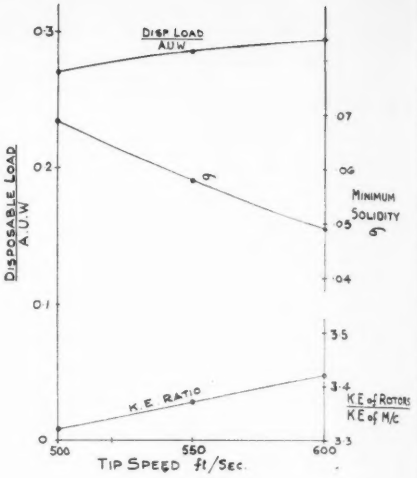

Fig. 22.
The effect of tip speed.
Power = 2,500 h.p.
Disc loading = 3.3
Minimum U/c. travel

The Air Horse undercarriage has a travel of five feet, which enables the machine to make an emergency landing in vertical descent without power and without relying on the kinetic energy of the rotors. The rate of vertical descent is estimated at 41 feet per second and the energy absorbtion, therefore, is approximately 12 times that corresponding to minimum A.R.B. requirements.

In providing a high absorption undercarriage the Company was guided by the following considerations:—

(*a*) That safety features independent of the pilot's skill are likely to be far more effective than those depending on a rather precise manœuvre requiring great presence of mind and experienced judgment.

(*b*) That loss of power is experienced often immediately after take-off, when there is no time for the pilot to make the required landing manœuvre. In fact, to reduce, if not escape, the danger at small heights over the ground, it is necessary to follow a take-off and landing technique which, apart from using maximum r.p.m., includes inclined

climb, as well as taking account of the prevailing wind. Such procedures militate against the main advantage of the helicopter, namely all-weather operation from strictly confined spaces. It is visualised that the helicopter, to do justice to its principal function and to simplify landing facilities and navigation, has to be able to take off and land truly vertically and to be independent of wind direction. These considerations apply more particularly under conditions of poor or zero visibility.

The freedom of choice in take-off and landing procedure has a direct bearing on cost of transport through the simplification of ground installations and conditions of approach and shortening of block time.

(c) To substitute effectively kinetic energy for undercarriage absorption capacity it is necessary to provide enough of it at take-off and landing.

A full analysis of energy transformation in vertical descent is complicated, but in *practice* (that is allowing for a normal degree of error on the part of the pilot) the available kinetic energy in the rotor must be a multiple of the kinetic energy of the machine in vertical descent. Some published data lead to the conclusion that the factor ought to be about five for adequate safety.

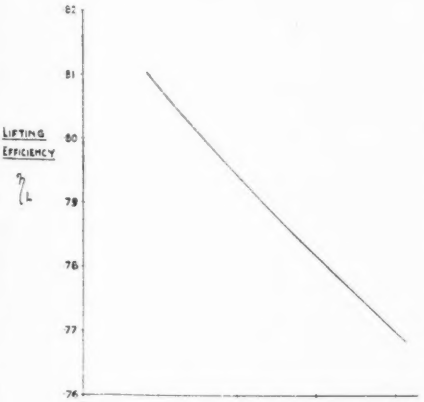

Fig. 23.

Lifting efficiency versus tip speed. Tapered twisted blade.

Disc loading = 3.5 lb./sq. ft.
Nominal solidity = 0.05.

Figure 22 shows that without special attention to this matter, we may expect in a well-designed three-rotor machine, a factor of three varying only little with tip speed.

To obtain the missing 66 per cent. of available energy we can either increase tip speed by 30 per cent. *keeping the same blades* or increase blade inertia by 66 per cent. with constant tip speed.

The former procedure will reduce the lifting efficiency by as much as 4 per cent., as can be seen from Fig. 23, giving lifting efficiency over tip speed at constant solidity.

The second procedure will add at least 6 per cent. to the empty weight. Although additional blade weight can, up to a point, be introduced at the most favourable location and blade weight will not go up in proportion to inertia, the increase in centrifugal force will affect further components of the machine.

On the other hand, the weight penalty of the long travel undercarriage is surprisingly low in the Air Horse. It is necessary to establish here that the undercarriage stroke is chosen so that the resulting ground reaction in an emergency landing does not penalise the airframe designed to withstand maximum flight loads and/or crash accelerations.

The complete undercarriage group in the twin-engined Air Horse is estimated at below 6 per cent. of all-up weight. Not more than half would be saved if ordinary undercarriage requirements only were fulfilled. The sacrifice for long travel amounts to barely 3 per cent. of all-up weight, which is less than the useful weight increase obtained by enabling the machine to take-off, hover and land at optimum blade angle.

It is evident, therefore, that a good case can be made for a long travel undercarriage at this stage of the art. Experience will show whether the amount of emergency energy absorption chosen by us is correct, or whether some intermediate value is satisfactory, since it is probable that in all cases some relief will be contributed by the "pulling up" technique, which converts the kinetic energy of the rotor into lifting power.

In this connection it is worth mentioning a popular misconception which has obscured the part played by the shock absorber in the weight balance.

In the Air Horse, where the shock absorber is a separate unit from the structural components of the undercarriage leg, the shock absorber is not expensive in weight. In fact, all three shock absorber units in the

Air Horse weigh about 1½ per cent. of the all-up weight and a reduction of shock absorber capacity to a conventional value would save barely ¾ per cent. of the all-up weight. It does not appear to be profitable to indulge in ingenuous but untried schemes of low weight shock absorption. It is in the structure where weight economy in design has to be practised. Here, as elsewhere, the choice of principal parameters is the most powerful means of producing components of minimum weight.

5. COMMENTS ON OPERATORS' REQUIREMENTS

From the point of view of this paper, requests made by operators may be classified into several categories.

(*a*) Many features which distinguish the Air Horse were introduced in response to operators' requirements. Among these are powerful, unfailing control and minimum interference, static and dynamic stability, accessibility of mechanism, ease of handling payloads, and enhanced safety and freedom from operational restrictions because of the long travel undercarriage.

(*b*) Every designer must admit that many troubles experienced by operators arise not from inherent difficulties, but merely from lack of foresight in the design. No purpose is served by covering up lack of attention and the remedy for such faults lies in better appreciation of the problems by the operators themselves and better co-operation between operators and designers. Specifically it cannot be denied that in helicopters some, although not all, vibration troubles fall into this category, especially those arising from resonant response to periodic impulses which, in themselves, are not intolerable.

(*c*) Some of the requirements put forward by operators are conflicting. Most improvements have to be paid for with money or weight, or both. To do justice to such conflicting requirements it is essential for the designer to be given some guidance of a quantitative nature as to the relative value of the different requirements. It is admitted that such information may be extremely crude at this early stage of practical experience, but crude information is better than none. The designer has to co-ordinate those design requirements which he can evaluate himself. For example, in the case of the Air Horse, we work to a rough rule by which the reduction of forward drag by one pound at 100 feet per second is worth three pounds of structural weight. Similarly, the reduction of structural weight by one pound is worth anything between 10 to 25 pounds sterling, according to utilisation. It will be desirable to have some guidance, for example, on the value of one pound of structural weight as compared with the saving of one hour of maintenance work per 100 hours of flight.

(*d*) Finally, there are requirements to which the designer is fully alive but which constitute real technical problems requiring systematic research and development, for their solution. Prominent among these are the following:

1. Simplification of control through use of automatics.
2. Much higher degree of automatic stability than anything hitherto achieved or envisaged.
3. Better mechanical reliability through improvements in basic elements, such as transmission and articulation.
4. Improved structural efficiency.
5. Improved aerodynamic performance through reduction of forward drag and development of improved blades, leading to increased speed mainly through delay of tip stall.
6. Elimination of vibration by new fundamental approaches.
7. Introduction of automatic safety devices, such as rotor speed limitation, conversion to auto-rotation, de-icing equipment.
8. Two-speed reduction gear.

In all these fields, progress will be determined by the effort invested in research and we all hope such research will receive assistance and sponsorship on a scale commensurate with the promise of the great benefits which the public expects from further developments of helicopters. There is little controversy among helicopter constructors either here or abroad about the aims and emphasis of further research. Operators will be inclined to stress the importance of main-

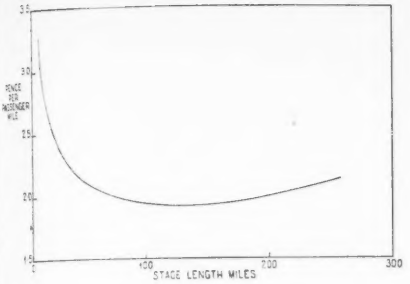

Fig. 24.

Air Horse passenger carrier direct flying costs. Effect of stage length.

Cruising speed = 116 h.p.h.
All-up weight = 17,500 lb.
Annual utilisation = 2,400 hrs.
Load factor = 100 per cent.

tenance, of further advances of control and stability and the benefits to be gained from a really impressive increase in flight speed for transport operations, and constructors are alive to the great improvements possible in weight economy through advances in structural efficiency of bearings, joints and gears. It is interesting to reflect upon such figures as the total weight of all ball bearings in the Air Horse, which is of the order of 700 pounds, or the fact that we were able to save nearly 200 pounds in the weight of wheels because the supplier had done enough research to determine their behaviour under excess loads.

6. POTENTIALITIES OF AIR HORSE IN CIVIL AIR TRANSPORT

The emphasis of this discussion has been put on actual achievements. The Air Horse is only now undergoing flight testing and cannot be expected to reach Certificate of Airworthiness standard for some months. Knowing the considerable reserves of strength and safety which our policy dictated, we have every reason for confidence. We have seen that this achievement is characterised by a percentage of disposable load of 32 per cent. in the freighter version, corresponding to 27 per cent. in the passenger version. Although this figure may drop somewhat because of additional operational equipment, it approaches the figure of 28 per cent. given for the Ambassador, which is a highly developed, conventional, fixed-wing aircraft. Such an achievement in a completely novel configuration means that the potentialities of the type are much greater.

The policy of our Company is to pursue development along the line of increased all-up weight with the twin-engine installation, preserving many of the existing components. Experience with the Air Horse research prototype will enable us to depart from the caution with which such a novel conception had to be approached. It is expected that the twin-engined Air Horse will have a disposable load percentage of 30 per cent. in the passenger version and 35 per cent. in the freighter version, with full operating equipment of approximately 800 lb.

We differ from the estimates given by Mr. Masefield.* I am unable to understand why an aircraft on a scheduled route between, say London and Birmingham, should carry about 2,350 lb. of operating equipment. But the matter does not end there.

The twin Merlin Air Horse will be able to carry its normal weight at Nairobi and, suitably equipped, will hover with full load at 15,000 ft. over the highest passes of the tropical Andes. On domestic and European routes it will be possible to increase all-up weight and provide further payload capacity. Ultimately, we would expect a twin Merlin helicopter carrying passengers on internal routes to have a disposable load of approximately 35 per cent., as compared with 22½ per cent. estimated by Mr. Masefield.

We may look forward to the maintenance of a ground speed of 120 m.p.h. against a

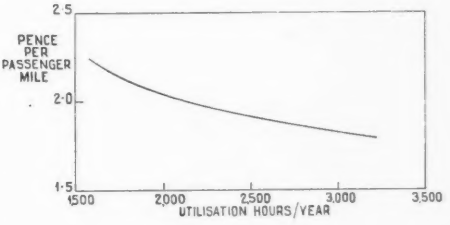

Fig. 25.

Air Horse passenger carrier direct flying costs. Effect of annual utilisation.

Cruising speed = 116 m.p.h.
Stage length = 110 miles.
All-up weight = 17,500 lb.

* MASEFIELD, P. G. Third British Commonwealth and Empire Lecture: Some Economic Factors in Civil Aviation. JOURNAL R.Ae.S., October 1948.

20 m.p.h. head wind, when called upon to keep up regularity on scheduled services.

Such prospects carry with them the promise of really competitive fares.

Discounting for the moment further development, present estimates of direct cost for the twin-engined Air Horse are of the order of 1.9 pence per passenger mile for 100 per cent. load factor, and a stage length of 100 miles. This estimate is based on a percentage disposable load of 30 per cent., and a first cost of 2½ pounds sterling per pound of all-up weight which is quite feasible, provided that a substantial part of development cost is borne by other than transport users of the helicopter. The utilisation is assumed to be 2,400 block hours per year, a figure which can hardly be called excessive. Most other assumptions are borrowed from fixed-wing practice and do not require much unwarranted guessing.

The load factor in helicopter transport must be considered without prejudice from fixed-wing experience. It will be greatly influenced by tariff policy and by the frequency of the service and must at present remain highly speculative. Even if we assume a load factor of 65 per cent. the direct cost per passenger mile becomes 2.66 pence.

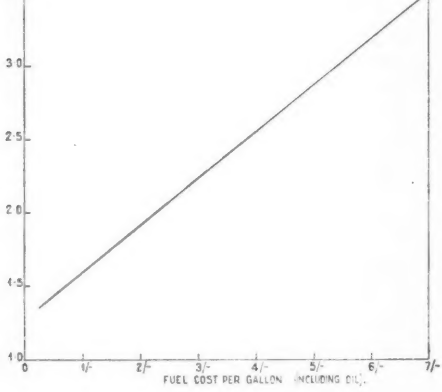

Fig. 27.
Air Horse passenger carrier direct flying costs.
Effect of fuel costs.
Stage length = 110 miles.
Cruising speed = 116 m.p.h.
Utilisation = 2,400 hrs./year.
All-up weight = 17,500 lb.

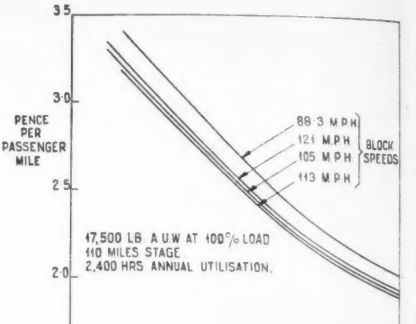

Fig. 26.
Air Horse passenger carrier direct flying costs.
Effect of load factor.
All-up weight at 100 per cent. load = 17,500 lb.
Stage length = 110 miles.
Utilisation = 2,400 hrs./year

Figures 24, 25, 26 and 27 show the effect of stage length, utilisation, load factor, and price of fuel on cost per passenger mile. These should be taken as illustrations of trends, rather than in absolute terms.

All that can be said at present about overhead expenses is that they must be inherently lower than those of fixed-wing aircraft, because of the basic features of the helicopter which require only a fraction of the ground installations and facilities essential for the fixed-wing operation. I believe that overhead expenses of 33 per cent. are a generous allowance which can eventually be reduced to 25 per cent. or even 20 per cent. Thus we arrive at an economical fare of less than 3.5 pence per passenger mile. I visualise the single fare between London and Birmingham to be 28/- compared with the present single first class rail fare of 37/9. On the basis of a cruising speed of 116 m.p.h. the scheduled block time of the journey would be 59 minutes. Similarly, a single fare between the centre of London and the centre of Paris would be exactly £3 and the journey would take two hours and two minutes.

Few people would disagree with me in expecting that if these figures can be obtained, and I believe them to be quite within our grasp in three to four years, a great volume of traffic will be carried by helicopter services over routes such as those mentioned above and I look forward to the

day when, from a helicopter station in the centre of London, twin-engined helicopters will rise every 20 minutes and carry 30 passengers to Paris, or Brussels, or Birmingham, or Manchester. This vision is one aspect of the greatest revolution in transport since the motor car. Combined with its other aspects this revolution will have a profound effect on the pattern of our lives.

7. ACKNOWLEDGMENTS

I pay special tribute to our Chief Designer and Managing Director, Mr. C. G. Pullin, and my colleagues, the Deputy Chief Designer, Mr. H. Bolas, the Chief Mechanical Engineer, Mr. K. Watson, and the Chief Test Pilot, Mr. H. A. Marsh, as well as to the able and devoted staff of the Company who have made the design and construction of the Air Horse possible.

The rotory aircraft world owes a great debt to our Chairman, Mr. J. G. Weir, for his pioneering devotion for the past twenty-five years.

8. CONCLUDING REMARKS

Many authoritative voices have been heard recently to the effect that in fixed-wing aircraft operation the development of flying machines has outstripped existing ground facilities and flight equipment. I would like to make a plea to all those concerned with helicopter operation to ensure that such a situation should not arise when the machines now in the course of development will be ready for operational duties. Much thought and development will be required to construct adequate ground installation for this purpose and the time has come for this work to be done simultaneously with the flight development of existing machines.

I also wish to stress the great influence exercised by regulations on both design and operation of rotating wing aircraft. Fig. 14 shows to what extent the airworthiness requirements influence economic effectiveness as exemplified to the effect of maximum lift factor on the disposable load of a helicopter. Similarly, operational regulations have an equally profound effect on the economics of helicopter operation. It is realised that the authorities responsible for such regulations have a great responsibility towards the public and cannot lightly abandon an understandable attitude of the greatest caution. The remedy lies in continued and intensified research, which should be directed towards the aim of binding the designer by the fewest, simplest and most reasonable restrictions to facilitate his task of producing economical machines.

APPENDIX

STRUCTURAL WEIGHT ANALYSIS

by

J. S. SHAPIRO and G. H. TIDBURY

1. NOTATION

a = blade section lift slope.

a_1 = coefficient of cosine term in blade flapping motion.

a_m = slope of lift curve in compressible flow.

a_o = slope of lift curve in incompressible flow.

b = No. of blades per rotor.

B = tip loss factor.

c = blade chord at any radius = $c_o(1 + tx)$

c_o = projected blade chord at rotor centre.

c_t = coefficient for centrifugal force.

c_l = coefficient for lift factor.

C_{Do} = mean profile drag coefficient for blade sections.

C_D = helicopter parasite drag coefficient.

C_H = rotor longitudinal force coefficient, see Ref. 1.

C_p = rotor power coefficient.

C_T = rotor thrust coefficient.

F_c = centrifugal force per blade.

F_N = numerical coefficient given in Ref. 1.

K_{rs} = weight coefficient.

l_d = nominal disc loading of complete helicopter.

M = Mach number.

n_1 = landing limit load factor.

n_2 = lift limit load factor.
N = number of rotors.
N_1 = number of long outriggers.
N_2 = number of short outriggers.
P = total maximum engine power at rated altitude I.C.A.N.
R = rotor radius.
t = blade taper = $\frac{c_{tip}}{c_o} - 1$.
T_n = numerical coefficient given in Ref. 1.
u = nominal tip speed at speed for rated engine power.
u_c = tip speed at design cruising condition.
u_h = tip speed at design hovering or vertical climb condition.
u_m = tip speed at design overspeed.
V_C = vertical climb speed.
V_H = horizontal speed.
W = all-up weight.
W_e = equipped weight.
W_{rs} = term in expression for equipped weight.
x = non-dimensional radius r/R.
α = rotor angle of attack, see Ref. 1.
α_T = angle of attack of tip section of blade at $\psi = 270°$.
δ = rotor drag (non-dimensional).
θ = pitch angle of blade element $\theta_o + \theta_1 x$.
λ = through flow ratio.
μ = tip speed ratio.
ρ = air density.
σ = nominal solidity of one rotor, measured at $x = 0.75$.
σ_o = solidity at root, assuming projected chord.
ψ = blade azimuth measured from downwind position.
ω = angular velocity of rotor.
η_L = lifting efficiency of rotor.
η'_T = transmission efficiency with cooling loss included.
η_T = transmission efficiency reduced by allowance for tolerance.

2. DESIGN PARAMETERS

The equipped weight of a helicopter can be expressed as the sum of a number of terms each depending on one or more of a set of design parameters. Since the enquiry is concerned with multi-rotor helicopters the design parameters are:—

(*a*) Maximum power.
(*b*) Disc loading.
(*c*) Nominal tip speed.
(*d*) Rotor solidity.
(*e*) Undercarriage stroke.
(*f*) Number of rotors and configuration.

For purposes of analytical treatment the various possible configurations are expressed by the numbers of long and short outriggers (N_1 and N_2). Pylons for tandem rotor machines are treated as short outriggers.

The treatment can be rendered more general by the use of further variables, the choice of which is more severely limited and which for any one investigation are usually fixed. These design assumptions are:—

(*g*) Rate of vertical climb.
(*h*) Lift factor.
(*i*) Transmission efficiency.
(*j*) Atmospheric density.
(*k*) Lifting efficiency.
(*l*) Cruising speed.

The equipped weight is first presented as a sum of terms each depending on the physical magnitudes which determine the design of particular components. The physical magnitudes are expressible by functions of the variables (*a*) to (*k*).

The weight terms, grouped into major structural components, are as follows:—

W_1	Power unit		Proportional to power
W_2	Transmission	W_{2a}	Propl. to power and No. of rotors
		W_{2b}	Propl. to total torque.
		W_{2c}	Propl. to power and length of transmission.
		W_{2d}	Propl. to power only.
W_3	Hubs	W_{3a}	Propl. to total torque
		W_{3b}	Propl. to centrifugal force per blade and total number of blades
W_4	Blades		Proportional to solidity × (radius)$^{2\cdot2}$ and No. of rotors
W_5	Tankage		Proportional to power
W_6	Controls	W_{6a}	Constant
		W_{6b}	Propl. to length of run to each rotor and No. of rotors
		W_{6c}	Propl. to centrifugal force per blade and No. of blades
W_7	Fuselage	W_{7a}	Propl. to all-up weight
		W_{7b}	Constant portion
		W_{7c}	Propl. to all-up weight and landing factor
		W_{7d}	Propl. to A.U.W. and lift factor

W_8 Outriggers	W_{8a}	Propl. to $\sqrt{}$(A.U.W. and landing factor) × (radius)^2
	W_{8b}	Propl. to $\sqrt{}$(A.U.W. and lift factor) × No. of long outriggers and (radius)^2
	W_{8c}	Propl. to $\sqrt{}$(A.U.W. and lift factor) × No. of short outriggers and (radius)^2
W_9 Undercarriage	W_{9a}	Propl. to A.U.W. and landing factor
	W_{9b}	Propl. to A.U.W., landing factor and (stroke)$^{1.5}$
	W_{9c}	Propl. to A.U.W., landing factor and stroke
W_{10} Furnishings		Proportional to payload
W_{11} Fixed equipment		Constant
W_{12} Pilot		Constant

Equipped weight $W_e = \Sigma W_{rs}$

Associated with each of the above terms there is a weight coefficient (K_{rs}) obtained by dividing the weight of the suitable parts of the Air Horse by the variables stated. In some cases the coefficients have been adjusted to take into account expected design improvements, bringing the results into line with the target figure for the twin-engined project.

The dependent physical magnitudes all-up weight, torque, centrifugal force per blade, radius and landing factor can be expressed in terms of the independent design parameters as follows:—

$$\text{A.U.W. } W = \frac{523.5 P \eta'_T \eta_L \rho}{l_d} \times$$

$$\times \left(V_c = \sqrt{V_c^2 + \frac{2.05 l_d}{\rho}} \right)$$

(An allowance is made for vertical drag equal to 2.5 per cent. of A.U.W.)

$$\text{Torque} \qquad Q = \left(\frac{550 P \eta_T R}{u} \right)$$

$$\text{Centrifugal force per blade } F_c = \left(\frac{c_l \sigma R^{1.2} u^2}{b} \right)$$

$$\text{Radius} \qquad R = \sqrt{\frac{W}{N \pi l_d}}$$

Landing factor is proportional to disc loading and inversely proportional to undercarriage stroke.

Of the independent design parameters and assumptions rate of climb and density depend on the probable use of the machine. In the results quoted 6 ft./sec. vertical climb is assumed outside the ground cushion at 5,000 ft. tropical summer conditions. Lift factor can be either a constant as in the draft Air Registration Board requirements or chosen to relate to the maximum lift of the rotors obtained in the stalled blades condition, when the lift factor is $n_2 = \left(\frac{c_l u^2_m \sigma}{l_d} \right)$

Transmission efficiency includes 4 per cent. error factor to allow for all uncertainties and manufacturing tolerances. Solidity and lifting efficiency can be obtained in terms of thrust coefficient as shown in the next section. Undercarriage stroke in this investigation has been chosen to render a constant landing load factor in the extreme emergency case of a vertical descent without power. This has to conform to the crash acceleration factor. This choice is a simplified interpretation of a number of considerations.

The design parameters which remain to be chosen are power, disc loading, nominal tip speed and configuration.

3. OPTIMUM SOLIDITY

For the blade section used as a basis for this work, the maximum L/D ratio occurs at a high angle of attack, consequently the optimum solidity for efficient hovering or vertical climb will be low. It is not permissible in the general investigation to use the most efficient hovering solidity as two other criteria have to be satisfied.

(*a*) That the tip angle of attack of the retreating blade does not become excessive in the normal forward flight range.

(*b*) That there is adequate collective pitch control available above the normal hovering blade incidence before the blade stalls.

Both these cases render a minimum value when plotted against thrust coefficient, the larger of the two values then becomes the optimum solidity to be used in the design parameter investigation.

Minimum solidity for forward flight

An expression is developed for the solidity required for forward flight at a given tip angle of attack of the retreating blade.

The method is based on Lichten's coefficient system of performance calculation.[1]

From this paper four simultaneous equations can be written.

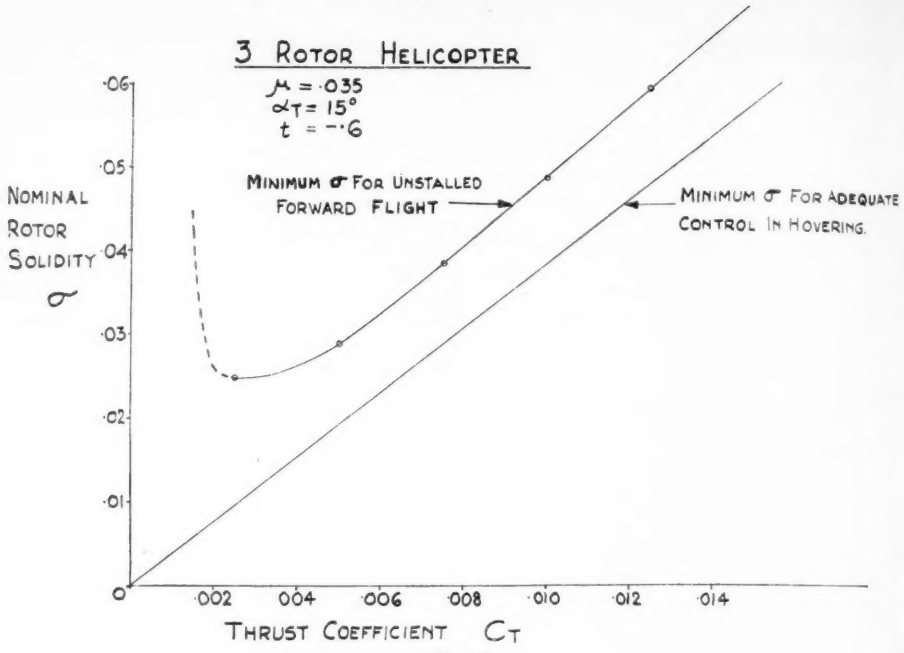

Fig. 28.

$$\alpha_T=\theta_0+\theta_1+\frac{\lambda+a}{1-\mu} \quad . \quad . \quad (1)$$

$$T_2\theta_0=\frac{C_T}{\sigma_0 a}-T_1\lambda-T_3\theta_1 \quad . \quad (2)$$

$$a_1=F_4\lambda+F_5\theta_0+F_6\theta_1 \quad . \quad (3)$$

$$0=-\frac{\lambda}{\mu}-\frac{C_T}{4B^2\mu\,(\lambda^2+\mu^2)^{\frac{1}{2}}}-\frac{C_H}{C_T}-\frac{\mu^2 C_{Df}}{C_T\cos^3\alpha} \quad (4)$$

In equation (4) the following approximations are made

λ^2 is small compared with μ^2 in $\lambda^2+\mu^2$

$\cos^3\alpha=1$

$C_H/C_T=a_1+\delta$ where $\delta=\dfrac{\mu\sigma C_{Do}}{2C_T}$

Also $\sigma_0=\dfrac{\sigma}{1+0.75t}$

Equation (4) becomes

$$\lambda+\frac{C_T}{4\mu B^2}+\mu a_1+\frac{\sigma\mu^2 C_{Do}}{C_T}+\frac{\mu^3 C_{Df}}{C_T}=0. \quad (5)$$

Expressions for θ_0 and λ in terms of σ can be obtained from equations (1), (3) and (5), when substituted in equation (2) a quadratic in σ is obtained, the solution of which is

$$\sigma=\frac{-Y-\sqrt{(Y^2-4XCC_T)}}{2X} \quad . \quad (6)$$

It can be shown that a sufficiently accurate solution can be obtained from the form

$$\sigma=-\frac{C_T}{Y}\left\{1+\frac{XCC_T}{Y^2}+\frac{2X^2\,(CC_T)^2}{Y^4}\right\} \quad (7)$$

Where $Y=\dfrac{aDC_T}{4\mu B^2}+\dfrac{aD\mu^2 C_{Df}}{C_T}$

$$+a\theta_1\,(G+H)-a\alpha_T H-\frac{aCT_3\theta_1}{(1+.75t)} \quad (8)$$

$$X=(aD\mu^2 C_{Do})/2C_T \quad . \quad . \quad . \quad (9)$$

$$C=(1+.75t)\,(1-\mu)\,(\mu F_4+F_5+1) \quad (10)$$

$$D=T_1-T_2-T_1\mu+T_1F_5-T_2F_4 \quad (11)$$

$$G=F_6\,(1-\mu)\,(\mu T_1+T_2) \quad . \quad . \quad (12)$$

$$H=(1-\mu)\,(\mu T_2F_4-\mu T_1F_5+T_2) \quad (13)$$

Fig. 28 shows the results of this calculation for

$\alpha_T=15°$

$\mu=0.35$

$t=-0.6$

$\theta_1=-0.1047$ radians.

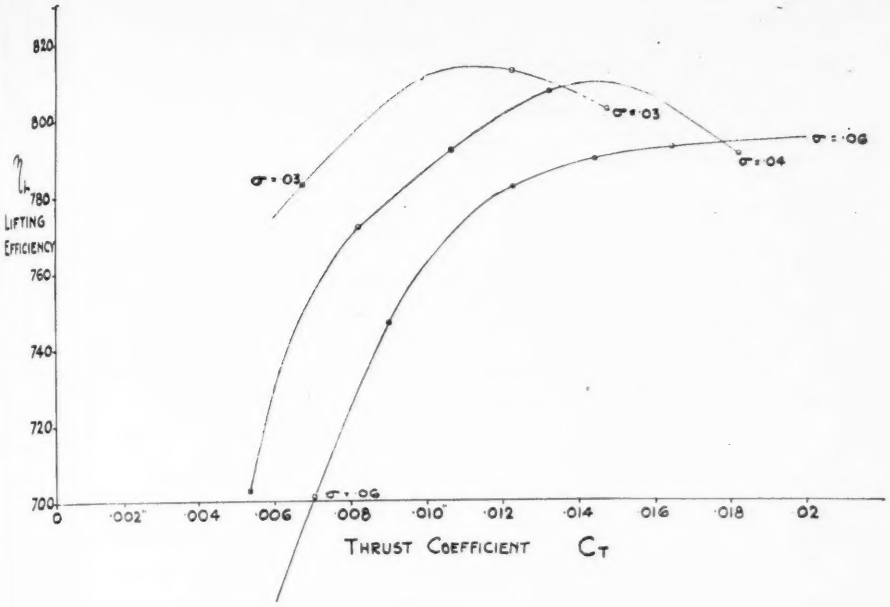

Fig. 29.
Tapered twisted blade.
Lifting efficiency chart. Hovering condition.

It can be seen that there is a minimum value for σ; for lower values of C_T the solidity rapidly approaches infinity. The theory appears to break down in this region, which is well below practical values of the thrust coefficient.

Minimum solidity for control in hovering

The assumption is made that the normal hovering thrust coefficient shall be 2/3 that of the maximum thrust obtainable if the blades could be stalled at every point along their span at the same tip speed. This latter condition is clearly a simplification, but it provides a simple numerical guide to ensure that control is available.

Since the lift coefficients of the blades will be the same for all solidities it is clear that there will be a straight line relation between the solidity and thrust coefficient, as shown in Fig. 28.

Usually this is not the limiting condition for choosing solidity as this line falls below the curve for the forward flight case; however, one case has been worked out where the curves cross over and since for other design requirements the assumptions used may vary it is necessary always to consider this limitation.

Tip speeds

Efficiency considerations lead to the choice of different tip speeds for cruising and vertical climb flight conditions. The choice is limited by engine performance in each design but, for simplicity, these tip speeds can be considered as constant proportions of the nominal tip speed.

In the present investigations the factors have been taken as unity. This choice may be necessary for some engines but the use of highly boosted and more especially derated engines, will widen the range of choice of tip speed for any power requirement, allowing more efficient operation. It is proposed to incorporate this feature in future investigations.

4. LIFTING EFFICIENCY

The lifting efficiency is obtained by using the complete method of Ref. 2. This gives values of the thrust and power coefficients for each blade angle chosen when the section characteristics and blade shape are known.

Since lifting efficiency $\eta_L = \dfrac{C_T^{3/2}}{C_p}$

Lifting efficiency can be obtained for any value of solidity and thrust coefficient by choosing sufficient values of nominal solidity and blade angle for the blade shape in question and plotting, as in Fig. 29.

Because of the length of the computation the chart is only obtained for hovering conditions, an adjustment is made to the lifting efficiency when the design criteria are specified at some positive values of the rate of vertical climb. It has been found that curves of lifting efficiency over climb speed are nearly parallel straight lines for various values of the thrust coefficient. Therefore, the correction of lifting efficiency for any one rate of vertical climb can be taken as a constant.

Lifting efficiency is calculated at a representative tip speed, as the effect of tip speed at constant blade loading is small. Tip speed affects only the lift slope of the blade section due to the Mach number effect and it has been found that the variation of this effect can be neglected for a wide range of

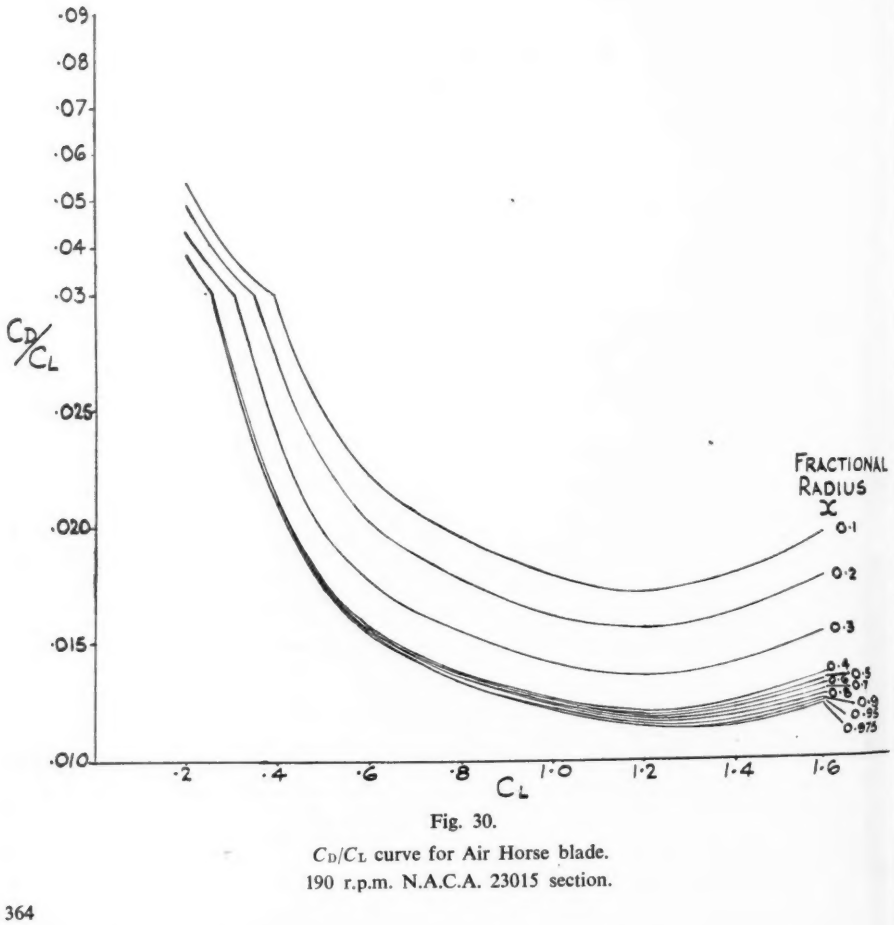

Fig. 30.

C_D/C_L curve for Air Horse blade.
190 r.p.m. N.A.C.A. 23015 section.

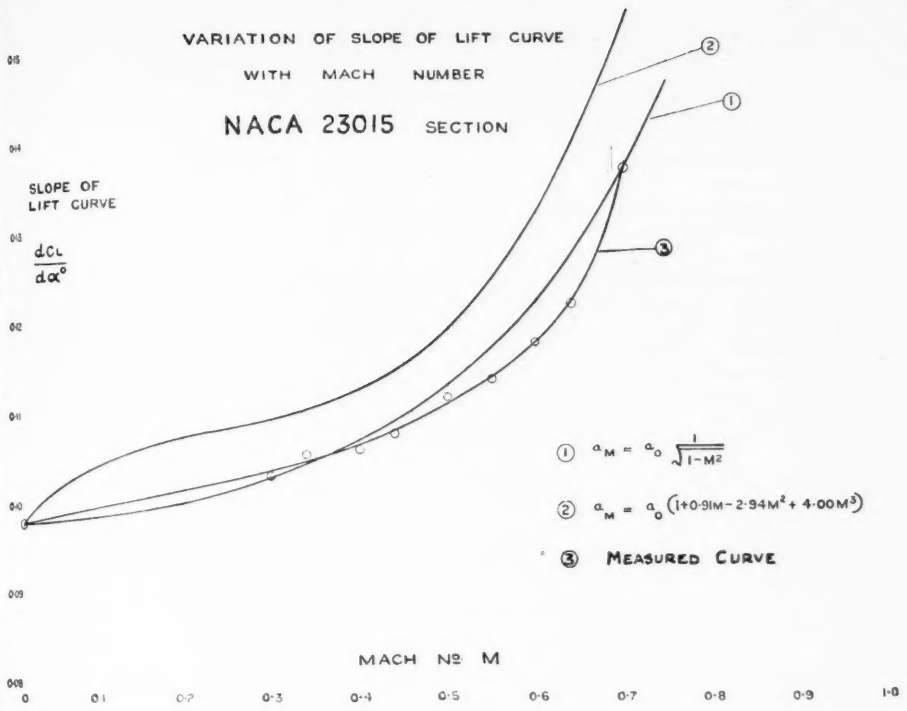

Fig. 31.
(1) Glauert formula. (2) Empirical formula (Sissingh). (3) Goethart.

tip speed. This must not be confused with the effect of tip speed on the lifting efficiency of any given rotor where the effect is large, due to change in thrust coefficient and therefore blade loading.

The L/D ratio used was obtained by adding 10 per cent. to the best low turbulence wind tunnel test results obtainable for the section used, namely NACA 23015. The curves used are shown in Fig. 30. The displacement of the curves is due to Mach number effect, except near the root where the profile is less efficient. The relation between lift slope and Mach number used is shown in Fig. 31 as the measured curve.

5. CONCLUDING REMARKS

This outline of the method used to determine the conditions for highest weight efficiency necessarily involves a multitude of factors. A critical examination of every assumption made and numerical value used would fill a volume, but a statement on the standard achieved in the authors' own judgment will help to focus criticism on essentials.

It is thought that the contribution of this investigation to the art of designing efficient helicopters consists of:—

(*a*) The method of co-ordination of available information leading to a rational choice of design parameters in a realistic manner.

(*b*) Use of detailed aerodynamic analysis, thus avoiding approximations which fail to do justice to the possibilities of aerodynamic refinement.

(*c*) Details of weight breakdown associated with laws of weight variation which,

within their sphere of validity, embody considerable design experience.

More specifically it is believed that lifting efficiency and minimum solidity are treated as fully as present knowledge justifies. The weight laws applied to blades, transmission hubs and controls are well founded on experience and/or rational analysis backed by fundamental relations. The power plant and equipment weights are realistic but outside the control of the aircraft designer. On the other hand, important parts of the airframe, and more particularly the outriggers and undercarriage, have been related to physical magnitudes in a somewhat arbitrary manner and merit closer investigation. The treatment adopted narrows down the field of speculation to a relatively small portion of the equipped weight.

The least satisfactory aspect in this study is the treatment of tip speed which has to be considered more fully in relation to compressibility vibrations, efficiency and in forward flight, it may then be possible to eliminate tip speed as an independent parameter.

6. References

1. Lichten, R. L. Helicopter Performance. Journal of the Aeronautical Sciences, July 1946.
2. Kaman, C. H. Aerodynamic Considerations of Rotors in Hovering and Vertical Climb Conditions. Journal of the Aeronautical Sciences, July 1943.

Discussion

A. Davenport (Westland Aircraft Ltd., *Fellow*): The request which had been made during the morning session for more money with which to develop the helicopter was not unusual; and the reason given, that the helicopter industry was not getting its share, was also not an unusual complaint. But some encouragement might be derived from the consideration that those who were concerned to buy helicopters would not always require that they be operated economically or at a profit. Sometimes a service was run at a loss in order to serve the convenience of the customers; and probably the helicopter would render the sort of service that could be run at a loss, or without profit, provided that the whole organisation of which it formed a part was run at a profit.

Mr. Peter Masefield, in his recent lecture, had suggested that the helicopter was not able to make journeys of more than 200 miles economically; at that stage the fixed-wing aircraft came into its own.

The installed power per passenger was rather low for it worked out at about 75 h.p. per passenger in the helicopter, whereas in its fixed-wing competitor it averaged 50 h.p. per passenger. That matter required attention, and improvement might well be effected by improved design and construction of rotor blades.

He disagreed with Captain Liptrot that replacements were excessive in the helicopter; in his experience with the Sikorsky S.51 there was a major inspection at 400 hours, and the cost of replacements was less than £100. That was a remarkable achievement, because that particular machine had been doing demonstrations and intensive flying.

Another matter in connection with operation costs was that of the consumption of fuel, which for the helicopter worked out at 3½ m.p.g., whereas in the fixed wing it averaged 7 m.p.g. Thus, there was much room for improvement, and he suggested that designers of helicopters might pay a little more attention to streamlining, particularly if the machines were to cruise at more than 100 m.p.h.

He supported Mr. Scott-Hall that designers should pay adequate attention to improving the stability of helicopters so as to make blind flying, map reading, and general navigation easier in adverse weather and other conditions. He also thought that the noise level in the helicopter at present was too high and should be improved, from the engine transmission, blades, and engine exhaust.

Norman Hill: He was a would-be operator of British helicopters.

Under present-day conditions development and production was a slow and tedious business for the manufacturers, and even to-day there was no British helicopter available with a full certificate of airworthiness. Furthermore, the experimental prototypes demonstrated so far had only a moderate performance and a poor capacity.

The insurance underwriters, suspicious of the helicopter and its mechanical complexities, and lacking experience and knowledge of the type, quoted rates for insurance which could only be described as harsh.

At State airfields landing fees were heavily against the type, although the wear and tear at such airfields caused by the helicopter was negligible when compared with fixed-wing aircraft. All these things weighing so unduly against it might prevent the helicopter, with its unique capabilities, from being properly exploited.

He would suggest that designers and engineers engaged in the British effort should *seal* their designs immediately practicability in performance and cost was apparent, and then let the operators who had the vision, the enterprise and the money, put the helicopter to the proper operational testing it required, if it were to secure its rightful place in commercial air transport.

Those interested in insurance underwriting should make themselves familiar with the helicopter and all its possibilities. This promising aircraft should not be burdened with heavy insurance rates without regard to its safety characteristics — characteristics which were clearly to be seen when in the hands of airline operators with an appropriate technical and financial background.

To those who were to-day framing legislation for the helicopter he would say—have safety by all means as their code, but frame and apply regulations with wisdom and vision so as not to hamper this new vehicle in its free development.

G. A. Ford (Helicopter Unit, British European Airways): As a pilot in B.E.A., he would definitely like to see some form of manual over-ride control with which the pilot could cushion a vertical landing in a restricted area, and also increase the pitch to compensate for the lower air density and the loss of engine power with height.

The fixed-wing aircraft instrument panel layout was the result of a number of years of practical experience, and the principles that governed that layout should be applied to the helicopter. In particular the blind flying instruments should be in front of the pilot and close together, even at the sacrifice of a little of the forward view.

Any improvement in stability would be a great asset to a pilot flying blind or by night.

H. Roberts (Department of Aeronautics, Imperial College of Science and Technology, *Associate Fellow*): There was a certain degree of over-optimism perhaps to be found in the Lecturers' approach to the problems of rotary wing aircraft. There were three main stages of development in any problem; investigation of the effect, the cause and the cure. The Lecturers had said a lot about the causes of helicopter problems, *e.g.*, the problems of stability and vibration, and the effects were fairly widely known. Thus excessive vibration led to discomfort during flight and fatigue failure of parts, while inadequate stability involved a higher degree of risk, and consequently reduced safety. What seemed to be lacking was that the Lecturers—particularly on the question of stability—had said little about the application of present-day ideas to provide improved answers to the problems.

The particular problem of vibration seemed to be getting the attention it deserved, and he congratulated the designers on their various ways of alleviating vibration troubles. But the "solution" to the stability problem offered by Mr. Shapiro was far from new, having been handed down by the earliest pioneers. Dr. Bennett's solution, involving the use of a fixed tailplane, gave stability only at forward speed, and was merely an adaptation of fixed-wing concepts. The Bristol machine apparently could only be stable over a limited range of forward speed. It seemed that all these so-called solutions were not really genuine solutions in the sense that they enabled them to achieve stability over the whole speed range without extreme complication or difficulty.

During the discussion it had been said that stability would be provided when it was required by the customer. He did not know whether or not it was proposed to provide it from a hat, like the proverbial rabbit, but stability would certainly not be provided just like that. Its achievement called for really hard work by a lot of people. In Great Britain there were a certain number of

experts, but nothing like the number that the situation required. In contrast to their own limited resources, in the United States there was intense activity by a large number of design and research organisations and it was probable that advances there could be more substantial than in this country; he could not help feeling that they were likely to be behind for a long while.

One of the roots of the trouble was that the teaching facilities in Great Britain for training engineers in this field were far too limited. In the new syllabuses of the "Aircraft Design" paper for the Associate Fellowship Examination the Royal Aeronautical Society, for the first time, was proposing to include specifically the rotary wing aircraft. He hoped that this, together with the activities of the Helicopter Association, might provide a fillip to the teaching organisations to extend their activities and facilities in this direction, so that eventually they might produce that body of designers and research engineers needed.

Whereas Mr. Fitzwilliams had said that the function of the helicopter was to deal with the low speed end of the speed-range, Dr. Bennett had said that his machine was designed, not so much for the low speed end, but for a high cruising speed. Perhaps they might be able to resolve that slight inconsistency.

Mr. Tye had said that he did not know of a solution of the general layout problem which gave reasonable fuselage shapes. If a fine fuselage were required there would be no difficulty in providing it. But the solution which looked best, so far as aerodynamical lines were concerned, was not necessarily the best solution for the overall aerodynamic performance. The morning discussion seemed to exaggerate one side of the picture.

In Mr. Hafner's first graph he had very high values of μ. The symbol μ did not generally exceed 0.5 or 0.6 and he would like to know what was meant by values of μ of 1, 2, 3 and 4.

In Mr. Hafner's equations there appeared a term which allowed for the deflection of the induced flow as it approached the disc, so that the effective angle of attack of the disc was altered. He was under the impression that deflections of this sort were not substantiated experimentally and there was a fair amount of argument—and it was very much a matter of opinion—as to whether there was any justification for using the deflection angle on a parameter.

Stability had been recommended in forward flight, but not necessarily in hovering flight. It seemed to him that the problem of achieving stability in forward flight was not difficult, and he did not think that anyone had said that it was. The difficulty was to achieve it in hovering flight, and he felt that it was rather begging the question to suggest that people really did not want it.

Pierre Renoux (S.N.C.A.S.E., Paris): A flying model had been made of a family of new helicopters developed by the S.N.C.A.S.E. which included some unorthodox features. A picture of it had been published. It had two tail rotors, which had advantages in connection with the control of the pitching and yawing components, and very good damping in pitching and yawing motion was secured.

G. E. Clair (Aviation Underwriter, The London and Lancashire Insurance Co. Ltd.): He welcomed the remarks of Mr. Norman Hill on insurance and noted that Mr. Hill hoped underwriters would enquire more closely into the helicopter situation. That request, to some extent, had already been met by the presence of two insurance representatives and much of value had already been learned.

If underwriters could have information as to the possibilities of auto-rotation in the event of engine failure, the loss of height necessarily involved and the heights at which any such failure could be handled safely it would be helpful. For example, he had gathered from Mr. Hafner's remarks that there was a possibility of landing the Bristol 171 with only a 50 yards landing run, which seemed quite good.

Mr. Hill had referred to harsh rates; he assured him that in the present competitive state of the market, underwriters did not charge more than they could help. Harsh rates were the result of bitter experience during the past few years, mainly on the Continent of North America, and some underwriters to-day even refused to look at the business. But whatever proposition was put forward, provided that the safety factors mentioned were clearly brought out, it would be found that the insurance market, instead of being rather nervous, would do all that was possible to help by covering this new and interesting development in aviation.

EVENING SESSION—Chairman Dr. H. ROXBEE COX

General Discussion

J. K. Williams (Air Registration Board): He emphasised Mr. Clair's point which was not fully appreciated by everybody, about the introduction of safety factors in order to reduce insurance rates.

The helicopter had definitely arrived as a successful flying machine, but the eventual helicopter passenger, the " man-in-the-street," still regarded the helicopter as a spectacular piece of ingenuity, capable of performing incredible tricks in the air, but not yet as a means of transport. In the next few years helicopter designers must concentrate on safety and on improving the efficiency of the design with regard to the percentage payload available, instead of increasing the complexity of the design in order to achieve spectacular records. He did not wish to belittle the splendid accomplishment of the Fairey Gyrodyne in attaining the speed record, but he felt sure that Dr. Bennett would be the first to admit that the attainment of that record was only incidental to the completion of a successful design.

From the safety point of view there were five major problems to be studied and overcome. They were:—

1. The helicopter at present was far too complex with too many moving parts. Simplification was needed to reduce the risk of failure of a component part which might be vital to the whole. They must make certain, by means of additional safety factors and check laboratory tests, that within the specified life, the parts, including gears, bearings and rotor blades, remained airworthy.

2. They had little knowledge of the loads which helicopters actually experienced during manœuvres in flight. The various types should be extensively flight tested with strain gauges to obtain a more accurate estimate of criteria for design purposes so that, not only could they be reasonably assured that the helicopter was safe for normal manœuvres, but also that the structure was as efficient as possible, without introducing undue failure hazards.

One of the most important problems was the possibility of the fatigue failure of a main rotor blade in flight. A great deal of research was necessary to establish adequate design safety factors and the technique of the laboratory fatigue tests. An excellent treatise on that subject had been written by Mr. Garraway in his Cierva Prize Memorial Essay.

3. The single-engined helicopter was a far safer flying machine than a single-engined aeroplane in the event of engine failure but, as Captain Liptrot had pointed out, a danger zone for engine failure for single-engined helicopters did exist. It could be eliminated by making the helicopter twin or multi-engined, or so designing the rotors that the pilot could use their kinetic energy to reduce the vertical velocity (before touch-down), or by the provision of a long travel undercarriage.

He agreed with Wing Commander Brie that all future helicopters in operation on scheduled routes should be twin or multi-engined types, the basic performance requirement being that the helicopter could maintain height on one engine under adverse conditions.

4. A reduction in the disc loading was needed. There they were faced with the paradoxical problem of reducing the disc loading and at the same time increasing the percentage payload to make the helicopter a competitive means of transport.

5. A successful technique for the complete blind flying of helicopters must be devised, with the attendant problems of the development of instruments and ground aids, reduction of pilot fatigue to the minimum, and overcoming the inherent instability of helicopters in their present stage of development. He believed that the B.E.A. Helicopter Unit would solve that problem successfully before long.

If these safety aspects could be successfully incorporated during the next few years, what were the future fields of operation for the helicopter? The whole trend of development depended on that. Surely they would not be satisfied with the limited fields envisaged at the moment, such as crop-dusting and spraying, Post Office work and shuttle services between the Scottish islands. Could they look forward to helicopters superseding fixed-wing aircraft on some of the major internal airlines in this country during

the next ten years or so? If not, he felt that helicopter development would be seriously retarded.

Dr. A. P. Thurston (*Fellow*): He sympathised with those who complained that money was not available for the development of this most important branch of aeronautics, but much development could be effected at little cost by means of models. For many years he had experimented with models, some of which did not conform at all with practice, and it seemed to him that with them many problems would be solved concerning the fluctuating forces which set up vibrations, and so on. He exhibited one of his models, which was stabilised like an ordinary aeroplane; it was dated 1939. It flew best when *not* pivoted at the root of the blade and he showed the optimum point of pivot. At times he had been in peril, by reason of the speed of the models in the air. Such blades spaced themselves when flown in multiple. He had used all types and shapes of blades *stabilised* and had determined by experiment the best point to pivot the blade. Models could be controlled remotely by means of a Bowden cable with a centre wire; differential control, pitch control and any other form of control of blade or engine could thereby be achieved.

A. H. Yates (College of Aeronautics, *Associate Fellow*), What was being done to narrow the range of danger heights between which, if engine failure occurred in a single-engined helicopter, a crash appeared to be inevitable? If an engine failed at a height below 30 ft. the landing could be cushioned by increasing the blade pitch. If an engine failed at a height above 300 ft. there was sufficient height for the auto-rotation of the rotor to be achieved, but at less than 300 ft. there was not that opportunity. It was desirable that, as soon as torque failed, the blades automatically set themselves to auto-rotating pitch, without time lag.

The pilot of a fixed-wing aircraft had to be on the extreme *qui vive* for only a few seconds after take-off, and had not to watch the controls so carefully when a comfortable height was achieved, but the helicopter pilot had always to be alert and was at a disadvantage in that respect.

Helicopter meetings seemed to attract people of such diverse interests that he wondered if they might gain, perhaps, if the meetings were a little more specialised.

F/Lt. J. R. Anderson (*Associate*): At a joint meeting of both rotary-wing and fixed-wing experts, it seemed appropriate to mention the combination of the two types of aircraft. So far the only reference to the type had been a mention of convertible aircraft by Mr. Fitzwilliams. The combination was now a practical proposition because of developments in gas turbines and in other technical spheres.

With convertible aircraft the landing and take-off difficulties of the fixed-wing aircraft could be overcome to a great extent and, for a given engine power, the convertible could show less than half the drag area, which meant higher speed. For heights below 8,000 feet, it meant that the convertible type could be operated at speeds which fixed-wing aircraft could not touch, and thus could fill the gap between the helicopter at the lower heights and the fixed-wing aircraft at high altitudes.

There were none of the vibration difficulties found in the helicopter because of the periodic forces on the blades, since the axes of the various airscrew systems were not at approximately right angles to the air flow.

They lagged behind with helicopters through insufficient support, and one speaker had suggested this was because of their low military value. The convertible type had high military potentialities and its development was of importance—possibly vital—to the defence of the country. It was to be hoped that those responsible would not bury their heads in the sands of complacency. The papers presented to the meeting had clearly explained the limitations of the helicopter, and he hoped that support, both financial and in other directions, would be forthcoming from the departments concerned.

Wing Commander L. P. Gibson (*Associate Fellow*): The view that helicopters were difficult to fly had arisen largely, perhaps, because of the attitude of those who could fly them already; they formed something like a "magic circle" or "closed shop." There were two cases recently in which pilots had learned to fly the helicopter after only 1½ hours dual.

The lack of real facilities for learning to fly helicopters in Great Britain was perhaps the difficulty at the moment. People came along for a ride and their first flight was just a novelty; they did not really learn anything from this.

He suggested that there should be established somewhere in Great Britain a

familiarisation course—not a course which would cost something like £300, but one which would include, say, five hours flying. When jets were introduced there was established in the Service a week's course, which included five hours flying; the whole idea being to dispel the "black magic" which had then surrounded the jet.

If helicopters were to be developed so that everybody could use them and could take-off from, and land in, their gardens, they must rid themselves of that "black magic" idea.

Squadron-Leader F. J. Cable (Airborne Forces Experimental Establishment, *Associate*): A middle course should be adopted on the flying of helicopters. They must not go to the other extreme and say that they were easy to fly.

As to the stage at which a pilot should first be allowed to fly solo, it was one thing to get into a machine and fly it around the aerodrome, when everything was working well, and put it back on to the ground without damage, but it was another matter to operate and look after it regularly and to meet the cost of repairing the damage.

Difficulties, or the idea that the flying of helicopters was difficult, had arisen in the early days largely because of the mental approach and the necessity to appreciate the co-ordination of the controls.

There was no difficulty about the engine-off landing problem and that bubble should be exploded. At A.F.E.E., Beaulieu, they had made 500 or so engine-off landings successfully from various heights during the past few months. The Sikorsky YR4 was in the nature of being an experimental machine. Tests had been made with it, with more or less success, and presumably test results with later machines would be better than those obtained with the YR4. When operating the YR4 at 2,700 lb. (the full weight was 2,800 lb.) in still air conditions they had cleared a 100 ft. screen and had come to rest within 125 yards. That was not a stunt, but had been done often; he had been responsible for more than a hundred of those landings. To those who were interested from the insurance point of view, he could say that helicopters could be landed in one piece, depending largely, of course, on the circumstances and the skill of the pilots.

The helicopter could not be used fully until blind flying was a practical proposition. At the moment it was possible, but he would not like to say that it was practicable. In his opinion the first requirement before blind flying could be made practicable was stability. The helicopter was not free of troubles in that respect, but the problems were not insurmountable. Given a stable aircraft and the development of one or two instruments, blind flying would be practicable.

W. M. Evans (Air Registration Board): Speakers so far had avoided mention of the power plant, but from recent discussions with helicopter designers it appeared that there was a feeling that a case could be made for a modified method of rating helicopter engines. The helicopter designers felt that they needed a power for hovering (which was say, 90 per cent. of the maximum power of the engine), a power higher than that for emergency conditions and there might be some third rating, such as a power limited by b.m.e.p. and r.p.m., at which weak mixture strengths could be safely used.

He had tried to obtain some collective idea, if such existed, as to how helicopters, particularly the new designs that were coming along, could be operated, and he had found it extremely difficult. It might be that, as with most new designs, the designers were more optimistic than other people, or alternatively, they feared their optimism. It seemed that, not only would helicopters take a far greater percentage of the maximum power of the engine for longer periods, in relation to the total period of flight, than would fixed-wing aircraft, but that the engine r.p.m. would tend to be narrowed down to within a tight band just below the maximum r.p.m. permissible for extended periods.

That meant that engines were going to have an exceedingly hard time in helicopters. Did the Lecturers think there was any possibility of the efficiency of the helicopter being improved to such an extent that it would no longer be necessary, a few years hence, to take these relatively large percentages of engine power from the engines?

J. Brocard (Chief Engineer, Bréguet Company, France): He expressed his thanks for the invitation extended to the French engineers to attend the meeting, and the pleasure it afforded them to attend.

The first Bréguet helicopter had been built in 1907 and this was the first helicopter to succeed in becoming airborne, leaving the ground complete with engine, equipment and pilot. In later years M. Bréguet did further work in that field and in 1935 built the

Gyroplane Laboratoire which secured all World records for helicopters. Before the 1939-45 War a third machine had been built, which he believed was the only machine in Europe with two rotors, an arrangement which gave very good efficiency. The new machine was powered by a 240 h.p. motor and the diameter of the rotor was 8.60 metres (28.2 ft.).

Group Captain G. V. Howard (Helicopter Association): He was interested in the use of helicopters for anti-pest spraying and dusting work and had made enquiries as long ago as December 1946 about insurance rates; he was quoted variously 12 per cent., 10 per cent. and finally 7½ per cent. Because of the lack of helicopters from British sources, it had not been possible to proceed with the scheme at that time, but having been promised a Sikorsky S51 helicopter for delivery in February 1949, he had approached the insurance companies again in July 1948 and had learned to his horror that the rates had increased from 15 per cent. to 20 per cent. It was explained to him that the large increase was caused by the high incidence of accidents to crop spraying and dusting helicopters in the United States. On making enquiries, he discovered that the accidents had occurred chiefly to tail rotors—not because of any mechanical defect in the rotor system, but on account of the rotors striking trees and hedges. His informant volunteered the information that the helicopter operators liked to get the chemical well into the corners of the fields and generally got as close as possible to the boundary obstacles before turning. In effect, the accidents were caused principally by careless or rash flying and he suggested that this factor should be made clear to the various British Underwriters interested in the insurance of helicopters engaged in crop culture.

Generally speakers had referred to the alleged difficulty of operating a helicopter. He had been permitted to take a short course on helicopter operation and mechanism, at an R.A.F. Centre, while on his retirement leave and, judging by the description of a member of the staff concerning the complicated nature of operation, he formed the impression that at least four hands and two pairs of feet would be required. In actual fact, he found that while it was true that the technique required was very different from that of flying a fixed-wing aircraft, there was no great difficulty about it and he formed the impression that the average individual would qualify for solo flying more quickly than in the case of fixed-wing aircraft, because of the impossibility of flying slowly in the latter.

The creation of these mysteries by the experienced few was similar to the nonsense "black magic" of the earlier flying boat pilots, who tried to make out that web feet were required to a fly a boat successfully.

N. E. Rowe (British European Airways, *Fellow*): The designers' figures were still rather unrealistic in that they were not backed by full measurements or prolonged experience; but on problems of stability and performance, engine-cut performance, and so on, it seemed that a good deal had been done, that those problems had been given real attention in design, and there seemed promise of getting what they wanted.

For civil use safe, reliable, economic operation was wanted. Safety, in the connotation of "civil use" which he had in mind, was perhaps best achieved by having multi-engines, and he hoped they would get away from all the difficulties of engine cut and of landing with no power. Machines must fly perfectly well on part power, and that was one of the things expected from the designer.

In reliable operation were included all the points of maintenance, flying blind, good stability and control and operation in all sorts of weather. Group Capt. Fennesy had spoken of navigation, a matter which was of great importance in the whole set-up. If navigation could not be effected precisely and automatically, they were in great difficulty.

The problem of blind flying had not received the attention he had hoped. The meeting had tended to talk about stability and control rather than the actual practice of blind flying, although all agreed that it was necessary. In Great Britain it was essential for regular operation to be able to fly blind with complete precision of operation in terms of navigation, and complete safety in terms of control and stability and the pilot fatigue factor. Mr. Ford had mentioned the instrument layout, and the work of B.E.A. had emphasised the importance of good layout for blind flying, so that the fatigue, which was inherent in the helicopter to-day, was reduced to the minimum.

Wing Commander Brie had made a very important point when he had urged that they must make the best use of what they knew already. Exactly the same sort of plea was made by Sir Henry Tizard in his Presidential

Address to the British Association in 1948; he had said they would probably do more in advancing the general economics of life at this stage by making use of the knowledge they possessed now rather than by applying all their effort to the finding of new knowledge.

The point made during the discussion concerning the provision of sites had not been taken up, although it was of great importance to operators. There was need for real drive in connection with the provision of sites. Another important point was that, since the helicopter was a short-stage vehicle, the number of sites in a given group system would be large, hence equipment, manning and so on of such places must be done on an economical scale.

There had been a fair amount of discussion on vibration. He had done a fair amount of riding in the S.51, and the B.E.A. pilots had done a tremendous amount of work. He would say that the vibration was rather high for comfort but not unduly so. The point had been made by one of the designers that they should set down a standard of vibration which the operator would be prepared to accept; that was important because it would give the designers some idea of the limit on cruising speed imposed by passenger comfort. Vibration was important, but he had felt that there was a tendency to over-emphasise it.

He agreed on the point made that the total amount of effort being devoted to helicopter problems in Great Britain was too small and that they should have more training of technical men.

Research with models was also important. There was a technique in connection with fixed-wing machines which used a sequence of calculations and model tests and correlation with full scale. A similar technique was needed for helicopters. As things were now, they had to build a full-scale machine and find out what it was like. They should know a great deal more about it at the model stage.

B. H. Arkell (The Fairey Aviation Co. Ltd., *Associate*) *contributed*: Opinions had been voiced from many quarters during the discussion on the controversial subject of whether or not the helicopter was difficult to fly.

It was generally agreed that in steady forward flight, apart from stability problems, there was not a great deal of difference between the rotary and fixed-wing aircraft, and it was on the question of hovering that the controversy arose. An examination in detail of the characteristics during this condition of flight might throw some light on the subject.

In the fixed-wing technique, discounting aerobatic manœuvres, the condition of flight calling for the maximum concentration from the pilot and the most accurate co-ordination of aileron, elevator, rudder, and power controls, was the hold-off and touch-down to landing, occupying a period of perhaps a few seconds.

If the fixed-wing pilot considered the amount of concentration and co-ordination of control he needed to employ during this short hold-off period in order to ensure that the aircraft touched down to a perfect three-point landing, he would have some idea of what was required to hold a helicopter hovering, in just exactly that position, over an extended period of time.

Co-ordination of the controls in the helicopter was no more difficult than on the fixed-wing aircraft and became automatic with practice, but there would always remain the concentration, which was a source of mental fatigue. This theory had been borne out in practice and agreed with the experience acquired in helicopter crop spraying, which was a particularly tiring form of flying.

C. M. Britland (Royal Aircraft Establishment, *Graduate*) *contributed*: Apart from the specialised and irregular uses of helicopters, such as crop-dusting, and looking at the possibilities for regular airline transport, they might learn much from studying Masefield's recent "treatise." Masefield was convinced that helicopters as they knew them now were of little value for this purpose when the block distance exceeded about 200 miles, both from the economic and effective speed points of view. If they accepted his analysis they should either design helicopters specifically for such a short range or else overcome their fundamental handicap of low operating speed.

The first alternative suggested to him that they should energetically develop the jet-propelled rotor principle, since it was at short-range that such a device had superiority over the present system. Even with present knowledge the evidence suggested that they could build a jet helicopter which would hold its own economically with a reciprocating-engine design over a stage length of about 150 miles, and they had not started to conduct serious research on jet-rotor problems yet,

whereas the reciprocating-engine was almost at the peak of its development. Many people were confident that the jet type would come out on top eventually and greater urge should be given to its successful development; they they should not wait for the Americans to prove its practicability. But perhaps it would be wise in the early stages to see how much noise would be acceptable over the peaceful English countryside!

The second alternative, of removing the handicap of low operating speed, could only be solved by the convertible aircraft in which, after take-off, the rotors were tilted through 90° to act as low-revving propellers while the aircraft was supported by small highly-loaded wings. He realised the complexity of such a concept, but this must be weighed against its many advantages. It could be the fastest form of inter-city transport for all distances up to 1,000 miles, except for the jet-propelled air liner at the longer ranges and it could combine the simple terminal requirements of the helicopter with the operational flexibility of a propeller-driven aircraft. For the critical take-off and landing operations at night or in bad weather, a convertible had the inherent safety of the helicopter and should practically eliminate the stacking problem. Such a machine, if proved practicable, would eventually outmode the present-day helicopter. Would it not be worth while, therefore, to examine the possibilities in detail at this early stage?

Major J. L. B. H. Cordes (*Associate Fellow*) *contributed:* Aeroplane pilots did not find helicopters difficult to fly because they were afraid of losing speed as it was only a matter of doing so at a different time of flight. Every time an aeroplane landed it had to lose flying speed before it could touch down. He thought it was the gradual change of behaviour of the controls, when merging forward flight to hovering, that the pilot found rather puzzling at first. In forward flight the stick and pedals handled very much as they did in an aeroplane, but when hovering their functions altered considerably. The actual loss of speed at this stage of instruction would not worry the pilot as he had already been taught to hover. The pilot was not afraid of losing speed while hovering as he had none to lose, and in any case the controls were so different under hovering conditions that the pilot found he was learning something entirely new and aeroplane habits did not worry him.

He had found that the comparison of the behaviour (not control) of an aeroplane to that of a helicopter was akin to a bicycle and that of a horse and there was no more difficulty in graduating from one to the other. The bicycle depended on its forward speed for its equilibrium, and a change of heading for its change of direction; whereas a horse (a nice one) could remain stable irrespective of speed, and would move forwards, sideways and backwards, and could even be persuaded to stay still, although attempts at hovering should be discouraged. The danger area too, to those on the ground, as with the helicopter, was in the vicinity of the tail.

The claim had been made that, in comparison with the aeroplane, the helicopter could not be stalled. Surely a wing, whether fixed or rotating, was stalled when the angle of attack was increased to such an extent as to induce a breakdown of the air flow over the top surface, resulting in a loss of lift? The action taken to prevent this with either type of aircraft was the same in effect; in the case of the aeroplane the angle of attack was reduced by putting the nose down, and in that of the helicopter by reducing the pitch of the blades. There was this difference, however; if the increase in the angle of attack were persisted in, the aeroplane would stall, and if there were sufficient height, recovery would be made even from an incipient spin. On the other hand, with the helicopter under the same conditions, even before the blades reached their full stall the mean lift was great enough to overcome the centrifugal force that kept the blades horizontal, leading to "overconing" and the collapse of the rotor—from which condition there was no recovery, from whatever height, and the question of when the blades fully stalled was not even of academic interest to the occupants!

Safety

(*a*) *Parachutes.* It would be interesting to know what research had been, and was being, done to render the use of parachutes with a helicopter more feasible. There were certain conditions that could be visualised arising in flight, such as partial collision with another aircraft, a blade hitting a large bird, blade or hub failure, or, with Service aircraft, effects of hostile gunfire, where the use of parachutes would save life. Instructions to "jump clear in such a manner as to avoid the main rotor" were inadequate and, to his mind, a confession that a successful

drill had not yet been evolved. The helicopter was flown more often than not, below "parachute height" but on those occasions when it was flown high enough to justify the carriage of a parachute it would be nice to know that use could be made of it easily if anything sufficiently serious occurred.

(*b*) *Reliability*. He would like to add every possible ounce of weight to the argument for at least two engines for commercial helicopters. He thought that one of the foremost and essential civil requirements of a helicopter was to be able to take short cuts with safety over built-up areas, rocky mountains, stormy seas or other unsuitable landing terrain. For this purpose it must be able to cruise at full load without losing height, on half its total engine power. It was also a requirement of the law pertaining to aircraft heavier-than-air. He would prefer the configuration of three engines with one rotor to three rotors with one engine. There was a practical comparison here with the aeroplane, where a tri-motored monoplane was obviously more reliable than a single-engined triplane.

G. H. Cumberbatch Willins (*Associate Fellow*) *contributed*: The transition from slow or hovering flight under power to autorotation with the minimum possible loss of height, following a power unit or transmission failure, should be regarded as absolutely fundamental to safety of operation. Had any tests been made to determine what proportion of the total height lost was needed for merely establishing "Autogiro" flow pattern and a stable rate of rotation from the "helicopter" state of operation? It would appear that this was a fraction of the height loss that must be accepted as inevitable, but it should be possible, by means of lower disc loadings and longer travel undercarriages, to save in emergencies the whole of that part lost in building up forward speed for a safe landing.

Mr. Hafner had stressed the need for a definition of the permitted level of vibrations to keep within an agreed threshold of comfort. This was important since prolonged subjection to certain types of vibration could be very injurious; and it would be advisable to take advantage of the latest medical research on the subject.

The remarkable safety record of the Autogiro had been referred to several times during the course of the discussion. It was interesting to recall that during their first ten years of development and establishment Senor de la Cierva's Autogiros were flown in every part of the world by hundreds of pilots of all grades of experience, in schools, clubs, by private owners and on commercial operations without incurring a single fatal acident; a record that must be unique in the history of Aviation, and one that would bear comparison with any other form of transport.

Dr. H. Roxbee Cox (*Chairman*): He had been particularly glad to see the French engineers and also to see so many who were interested in the insurance side of the helicopter business at the meeting. One of the diagrams in Wing Commander Brie's paper was important from the insurance point of view; it showed how easy it was to walk into moving parts of a grounded helicopter, thereby damaging oneself and the helicopter, so that the insurance charge would be quite appreciable unless the greatest care were exercised.

One of Mr. Shapiro's diagrams, seemed to show that, if the number of rotors were increased on one of the multi-rotor machines, the ratio of disposable load to all-up weight tended to become asymptotic. That was puzzling. There was a clear difference between gaining further disc area by increasing the number of rotors and achieving the same result by increasing the area of each disc. It seemed to him that the former was more expensive in structure weight than the latter, and he would like to know why he appeared to be wrong on that point.

The Lecturers' Replies

WING COMMANDER BRIE

The criticisms which he had made arose from a close association with, and experience of, so-called modern equipment. If they looked back a little and delved into the nature of that equipment, no doubt they would get on to firmer ground. In the first place the Sikorsky S.51 was of American origin. Secondly it was a modified version of an aircraft conceived in 1942 for Service

use, and soon after constructed in quantity under the stress of war conditions. Thus, although considered modern in the sense that it still had no more recent competitor, it was in fact much out-of-date compared with a completely re-designed version incorporating those obvious refinements resulting from "know-how" which could now be produced. It was remarkable that the S.51 was so good.

On the other hand and despite the rapid advances made elsewhere in the rotary-wing art during the past ten years, it was only comparatively recently that in Great Britain the potentialities of the helicopter had received anything like sufficient official attention and support. It was all very well blaming the war for this state of affairs, but in view of their pre-war achievements it ill behoved them to rely on such a flimsy excuse. Now somewhat tardily they had seen the light, and there were heartening indications that an effort was being made to make up as speedily as possible some of the leeway lost.

In this the B.E.A. Helicopter Unit was making a valuable contribution. The objective behind the acquisition of American equipment had been twofold. Firstly to ascertain the operational characteristics of the helicopter: whether, and in what manner, it could best be used: to study the economics of scheduled services: and to discover the problems, limitations, and difficulties. Secondly they wanted their efforts to act as an incentive to the British Industry to produce something which could be used with satisfaction. British European Airways now had over twelve months' experience in handling the Sikorsky S.51, and although current proposals for 10, 20, and even bigger passenger-carrying helicopters were attractive to contemplate, there were advantages to be gained by not trying to run before they could walk. The British Helicopter Industry had yet to acquire that valuable background of design and constructional experience based on past achievement. For the time being it would be something to shout about if only someone in Great Britain could demonstrate a prototype capable of performing no less efficiently than the S.51. On the other hand the operator could not acquire the desired standard of basic knowledge and experience unless he had the goods to handle. So that his criticisms arose from the deficiencies which he and his colleagues in B.E.A. had found in the equipment they were using. He saw many opportunities in a meeting such as this of pulling themselves to pieces: in fact he recalled a fairly recent article in the JOURNAL of the Institute of the Aeronautical Sciences showing how aeroplane interests got together and did exactly the same thing—but more so. They had competent technicians, engineers, and pilots, but it was up to the Industry to produce something worthwhile before expecting that additional encouragement in the shape of orders which normally followed solid achievement.

The point made by Group Captain Howard, who had asked why the British insurance companies should base their rates on what happened in America, was a good one. In B.E.A., in the course of twelve months' operation, they had not had to replace even a split pin as the result of an accident. That was a fact, and it was an achievement. Perhaps they had a better appreciation of the limitations of what they were handling.

He did not think it was easy to fly a helicopter. He knew of no other aircraft which was so easy to fly as the C30 Autogiro. When he took the first prototype to Martlesham Heath for its Certificate of Airworthiness tests he had sent off three pilots without giving them any dual instruction; but that could not be done with the helicopter. During the evolution of the helicopter some very desirable Autogiro characteristics had been lost, and they had to retrace their steps a little.

With regard to the provision of landing sites in city centres, a point raised by Air Commodore Primrose, they must be careful not to put the cart before the horse. It was of no use having the sites unless they had the aircraft. But he believed that Westland Aircraft and others were doing their best to fill the gap.

What they wanted was not only a helicopter with acceptable flying and performance characteristics; they wanted also the advantages resulting from the healthy stimulus of competition. He felt quite sure that then the economics of the problem would look after themselves.

CAPTAIN LIPTROT

He agreed that what he and Wing Commander Brie had said in their papers was rather coloured by what they had at

present. They were using the equipment that was available, and from their experience of it they were trying to point the way and were trying to help others to appreciate what was being done in Great Britain in developing the helicopter. The British designers and constructors were showing that they were giving good engineering in the British helicopter. They were aiming at long life in the working parts, which meant low maintenance costs, and they were designing so that whole components could be taken out, repaired and replaced. Such factors showed that the British-designed helicopter was a sound engineering job; and the designers and constructors at the meeting had answered most of the questions put to them in the papers.

On the question of insurance rates in Great Britain, which appeared to be based on the accident rate in America, the accidents were not due to any intrinsic defects in the helicopter. So far as he was aware, in the whole development of the helicopter only seven people had been killed. That was a very low figure, and the helicopter was the only means of transport which in its early years of use had such a good record. Also on the credit side was the fact that the helicopter, in the two or three years of its operation, had been instrumental in saving well over 100 people.

They now had three helicopters of British design. Helicopters could not take their proper place in aviation until somebody built them in numbers. By giving the constructors the incentive to get a production line going, they would give enormous help to the development of the helicopter. The mere fact of getting a production line running would put the machine on the market; and once it got on to the market, increasing numbers would be sold. When they reached that stage, down would come the price, and then it would become economical to the operator.

DR. BENNETT

Mr. Yates had asked about the danger from engine failure at a height of less than 300 ft.; he happened to be visiting the Sikorsky Company in America on an occasion when there was an engine failure in a helicopter while hovering at a height of about 50 ft., and at a time when it was thought that 50 ft. was an unsafe height at which to hover. It was demonstrated on that occasion that that height was perfectly safe; the pilot had landed the machine and nothing much happened to it, except that the nose wheel was slightly damaged. There was no doubt that hovering at a greater height would be quite safe if the pilot took the proper action. It was advisable, however, not to rely entirely on the skill of the pilot and to incorporate the Gyrodyne features of low pitch, low rotor power and low disc loading. It was hoped eventually to ensure that a safe emergency landing could be made from any height by utilising the kinetic energy of the rotor before touchdown.

Mr. Roberts had referred to alleged inconsistency, in that the helicopter was required to have a high cruising speed for certain purposes but not for others. There was no inconsistency about that. He thought that the Gyrodyne principle of independent propulsion would, in the future, enable considerably higher cruising speeds to be attained and that the development of blade tip jets would result in an improved slow-speed performance. It was manifest that those features, far from being incompatible, could be combined, and, as development work was now at an advanced stage, it would not be long before rotary wing aircraft showed a marked improvement at both ends of the speed range.

He agreed with Mr. Williams that the present helicopter had too many moving parts. Simplification was needed, not only from the safety point of view, but to reduce maintenance costs. This was possible with the torqueless rotor which, with the absence of mechanical transmission, would enable rotary wing aircraft to be operated reliably and economically on scheduled airline services both in built-up areas and over water.

In reply to Mr. Evans, helicopters which were required to hover for long periods should either have an adequate reserve of power or be confined to operations where an engine failure would not be dangerous. Gas turbines, which might have to be incorporated in future helicopter designs simply for no other reason than that no suitable reciprocating engines would be available, offered certain advantages to the helicopter designer, one of which was that the helicopter could be designed to climb away vertically even if one engine failed.

MR. HAFNER

The references to blind flying equipment brought him back to his question concerning the need for standardisation of controls. They could not get on with the design of helicopters if they did not know what was needed. His Company had built a number of mock-ups during the past few years which had been changed considerably from time to time, mainly because of the uncertainty as to what was needed. There was a definite need for an early agreement on standardisation.

He sympathised with Mr. Tye's feelings about present-day helicopter configurations, but they should remember they had only just started on this new venture. There was consolation in the fact that in this instance at least they did not depend for safety on the maintenance of speeds of the order of 100 m.p.h. The latter was something really worthy of rebellion. He thought that the tandem rotor configuration contained a fair measure of features with soothing effects on engineer's instincts. It was symmetrical, had a small frontal area and would look not unlike a streamlined railway coach that had decided to take the air.

He felt that the real solution to the stability of the helicopter was essentially a simple one; he did not think the solution would be a gadget, but that there would be a sort of anti-climax. There was obviously a need for stability in forward flight but when hovering, the pilot was concerned with accurate control and had to maintain his position with regard to a point on the ground and, therefore, would not miss very much stability in that condition of flight. He felt that stability in forward flight would be obtained most easily by the conventional use of the tailplane. He had pointed out that within a certain speed range the Bristol 171 could be flown with hands off the controls. He hoped to be able to widen that speed range.

As helicopter engineering was developing rapidly and becoming progressively complex, it was important to prepare for the education of the young people now, and to ensure that this education was thorough.

The figures which Mr. Roberts had read in the graph on tip speed ratio as 1, 2 and 3 were actually 0.1, 0.2 and 0.3. The factor ζ did not refer to the deflection of the induced flow before the disc, but to the curvature (or the distribution) of induced velocity at the disc ζ was defined in Ref. 1.

The technical developments of the helicopter and its ground equipment were interdependent. Thus, for example, the size of a helicopter and certain of its design details (*i.e.* undercarriage) were probably controlled by the rotor stations employed and *vice versa.*

He could not agree with Wing Commander Brie that in the interest of safety in emergency landings it was particularly desirable to keep the rotor disc loading below 2 lb. per ft.^{2}.

It had been shown that the Bristol Type 171, notwithstanding the fact that its disc loading was over $2\frac{1}{2}$ lb. per ft.^{2}, had excellent landing characteristics.

Dr. Bennett had stated " helicopters which are rough in operation at high pitch in forward flight are usually quite smooth at the same forward speed in auto-rotation." He was surprised to hear this because he was of the opinion that collective pitch (or λ) was not a major factor in rotor vibrations. He could point out that the vibration level of the Bristol 171 was very low throughout the entire flight envelope. It was independent of λ, *i.e.* flying the aircraft in a flat glide and in low rotor pitch (which corresponded to the Gyrodyne condition of flight) was no better or worse than flying level or climbing.

He had come to the conclusion that the important speed limiting factors of a rotor were:—

Tip speed ratio
Basic lift coefficient
Mach number of the advancing blade tip
Coning angle

as could be seen from his paper.

He thought the range of danger heights had now been reduced practically to nil. He did not think the automatic reduction of pitch in a power failure was desirable, he thought it was dangerous, especially at high speed and near the ground. There was no need for a hurried reduction of blade pitch in a power failure, except during hovering at night, when every pilot instinctively would be alert and ready for an emergency.

The landing run of the Bristol 171 was practically nil; the forward speed was fully absorbed during the 10 seconds hovering prior to landing. Those auto-rotative landings were very comfortable; and he joined with others who urged that they might now safely dismiss outmoded ideas on auto-rotative landings.

In the design of the Bristol 171, great efforts were made to effect real simplification of components, not merely in order to make the aircraft cheaper to buy, but to reduce maintenance costs and to increase safety.

With regard to the auto-rotative landing shown in the graph, the glide, with the engine idling, began at about 5,000 ft. and at a height of 100 ft. the engine was switched off; so that throughout the whole descent the rotor was not driven by the engine.

He felt strongly that the helicopter might well supersede the fixed-wing aircraft for use on internal airlines. He did not agree with Mr. Masefield's view that the helicopter would serve for journeys up to 200 miles only, beyond which the fixed-wing aircraft would take over, but thought that the helicopter would serve for journeys up to about 300 miles.

Mr. Shapiro had suggested that the tandem rotor arrangement was only marginally better than the side-by-side arrangement and, therefore, inferior to the three rotor configurations. He, on the other hand, had found that the weight and drag of an outrigger structure for side-by-side rotors were extremely high and, therefore, the tandem rotor configuration was by far the best one for large shaft-driven helicopters.

Mr. Shapiro did not think the benefit of tip speeds beyond 550 ft./sec. was large. That was true for the hovering rotor. Many people, however, had pointed out the need for a high cruising speed and this could not be achieved without a high blade tip speed. The best performance of the Bristol 171 was obtained at a tip speed of over 700 ft./sec. and he thought this figure would increase as the art advanced.

MR. SHAPIRO

Mr. Tye was dissatisfied with the present state of knowledge on the subject of fatigue conditions in rotor blades. Long ago, Autogiro blades were designed on the scantiest information but the genius of the early workers Glauert, Lock and Cierva provided a basis for practical design. Studying subsequent investigations conducted by the R.A.E., he had been struck by the experimental confirmation of a brilliant approach. Autogiros had been flying for thousands of hours without a single failure attributable to blade fatigue. To-day analytical methods had been refined and measurements confirmed existing analysis even more closely.

There was no cause for lamentations in this field and he thought they knew as much of blade fatigue loads as they needed considering how little they knew of the behaviour of structures under prescribed fatigue loads. This shifted the emphasis to laboratory fatigue testing. But even there they could learn more if they heeded Sir Henry Tizard's and Mr. Rowe's advice on using existing knowledge. Some designs were amateurish and it was not surprising that failures had created the impression of lack of knowledge. Was this ignorance really necessary?

Mr. Fitzwilliams wanted talented volunteers from the ranks of aircraft engineers and many speakers seemed to want to go even further and breed a special race of helicopter designers. He disagreed: let them have *engineers*, craftsmen of the bench, the board, the laboratory and the desk, thoroughly familiar with fundamentals. Helicopter design was far too specialised an art to be taught at colleges, which should avoid specialisation *so far as possible*. Engineering applications should mainly serve as examples which, to be truly instructive, must be good, time-tested examples. He could not think of a worse example than the present-day helicopter.

Specialisation in helicopter design required a co-ordination and maturity of knowledge which could only be achieved in practice and through practice, unless they wanted young men capable of indulging in large scale scheming but incapable of attending to detail.

If specialisation were necessary let it be directed to types of activity rather than particular application. There was a case for vibration engineers, gear engineers and the like. He would like to create the profession of "stress physicist" and perhaps "fatigue engineer."

Helicopter design was a field wherein it was essential to discourage idle speculation by constantly keeping in mind the supreme question: how much? Opinions not expressible in quantitative terms were often worthless. Not only did the helicopter share with all aircraft the three-dimensional limitation due to its weight sensitivity, but it filled an intermediate gap in communications threatened on both sides by surface transport and fixed-wing aircraft. It must score in economics or be confined to a few

specialised duties. Economics was concerned with narrow margins of profit and loss.

To illustrate what was meant by a quantitative approach, he would select a few topics from the Discussion.

It was not very important whether helicopters were difficult to fly: but how long could they be flown by the average pilot under given conditions such as low visibility or rough weather? What was the fee for a course to reach acceptable standards? What was the salary of a professional helicopter pilot? Ships had been difficult to sail for thousands of years. This fact never endangered the future of shipping, but they could not accept a dinghy requiring as much seamanship as an ocean liner. Piloting must be related to the type of machine and its tasks.

This brought them to the demand for stability. The Air Horse had some stability but much more was wanted. Broadly, he shared the stability enthusiasm of Mr. Scott Hall and others, but felt that Mr. Fitzwilliams had put the matter in a better perspective. Some time ago he had come to the conclusion that it ought to be possible to make stability "to measure" and suggested that this approach should be investigated. The suggestion was taken up by Dr. Sissingh of the R.A.E. and his work led to results summarised in his recent lecture to the Helicopter Association. Those results, reinforced by information from the United States, threw the ball back to the operators. If they specified stability and control in quantitative terms they should get them without undue weight, price, or delay.

To specify those things quantitatively was not easy. There were several kinds of stability, each capable of variation over the range of forward speeds, but intensive research should start at once. An existing "unstable" helicopter should be equipped with instrument-controlled automatic devices capable of the widest variation in parameters. When this information was available the mechanisms adopted to incorporate the required characteristics would vary in each case. In the Air Horse with its power-assisted control it might well be that gyroscopic devices would fit in very well with its servo assisted rotor controls.

He had already stated his view that "complication" and the "number of moving parts" were rhetorical, rather than engineering, terms. What was wanted was cheap maintenance. The simplest thing of all was a sealed box!

Safety was measured by the insurance rate which, presumably, was related to the accident rate.

Here a quantitative approach required the intervention of statistics, and guessing was inadvisable. Some speakers were worried about structural and functional safety but he could not see much evidence to support such an anxiety.

It appeared that insurance rates soared because of a number of accidents entirely due to carelessness. In such circumstances, the appeal to the designer should be to make pilots' errors unlikely. The Air Horse went a long way in this direction because of configuration, size, and undercarriage design. Insurance interests would find the elimination of the "danger height" and the absence of a tail rotor of particular interest. With the exception of a twin-engined installation, most future tasks were steps towards elimination of pilot's error through automatic devices.

Mr. Williams seemed to think that reduced disc loading enhanced safety and reduced the payload. Neither, he thought, was true in general. Reduced disc loading led to more powerful control, higher maximum lift and generally more chance for good or ill, depending on the skill of the pilot. The effect of disc loading on payload was complex and had been discussed in his paper.

He thought that in a machine destined for public transport, such as the twin-engined Air Horse, the engine would be used much in the same way as in fixed-wing transports. Other machines would have some more severe and some less severe, duties than transports and small machines would be as unpredictible as small aircraft. On the whole, in adequately powered helicopters, the engine was no more heavily loaded than in equivalent aircraft.

Moreover, there was not so much difference between helicopters and fixed-wing aircraft in installed power per passenger as Mr. Davenport thought. Where duties were comparable, such as in medium transports, both required about 100 h.p. per passenger. Wide discrepancies existed when duties were ill-defined, such as in personal aircraft. Fuel consumption in m.p.g. per passenger, therefore, was inversely proportional to cruising speed in transport aeroplanes and the ratio might be

8:6 or 9:6 in favour of fixed-wing aircraft. When delays, caused by traffic control, were included the helicopter scored for short journeys.

The necessity for an undercarriage had been questioned. He thought it was like questioning the necessity for doors in a house which were only used for getting in and out and had no function in the process of dwelling. The helicopter was no different from the fixed-wing aircraft in this respect but, because of its shorter range, the undercarriage was used much more often in a given number of flying hours. It was take-off and landing which distinguished the helicopter and the undercarriage was an essential part of it.

The difference between a fixed-wing and a helicopter undercarriage was primarily in the take-off run and, therefore, mainly affected the wheels. In their experience wheels could be much smaller in a helicopter because fixed-wing wheels were designed around their brakes. In the Air Horse the wheels weighed one per cent. of all-up weight. It would be difficult to improve on that with any device, conventional or otherwise. But the structure must include a tripod with a broad base for ground stability and that was where much weight was generally spent. The wisdom of meeting emergency conditions by means of undercarriage shock absorption had been discussed in his paper. Even if they considered normal operation only, both fixed-wing aircraft and helicopters *could* be landed very gently; whether they would land gently, when traffic schedules had to be maintained, only statistics would tell. He doubted it.

Some questions asked and criticisms advanced would vanish automatically when sizes increased. He suspected that this applied also to Mr. Rowe's comment that designers' figures were unrealistic. Weight always went up in flight development to operational standard but increase was greatest in items of equipment and, therefore, proportionately smaller in larger machines.

It had been suggested that more attention should be given to model research. From his experience and the general rules governing model research, he had been led to believe, paradoxically, that the reason for the relatively small use made of model research in helicopter development was not that they knew too little, but too much. Model research would always be confined to enquiries into *isolated* problems. This was fundamental and was due to the laws of similarity which could only be met in one respect at a time. There were few urgent isolated problems in helicopters about which they knew too little for *design purposes* at this stage of refinement. Where such problems were encountered, as in the three rotor configuration in forward flight, model tests were made and proved relatively straight forward and instructive. To-day's problems in helicopter design were composite problems. Models could hardly be expected to answer such questions as how to specify required stability, what were pilots' reactions to control characteristics, or how to achieve smooth rotors. In such matters model results could be definitely misleading and many a designer had been tempted to vow never to use models again. Nevertheless, model methods could be fruitful and more research would require more model work.

Dr. Roxbee Cox had asked why the disposal weight percentage continued to grow when the number of rotors went up. Let them first agree that this was a speculation to which the graph given in his paper was not a reliable guide. All such graphs, more often than not, lost their validity when pushed to the extreme. His speculation on the graph was that the percentage of disposal load approached a constant. It stood to reason that in a hypothetical machine with 37 rotors (Jules Verne's number), each rotor was of the same value structurally and both additional lift and additional structure were independent of the number of rotors.

Increasing the disc area by increasing the size of each rotor was quite a different matter and the percentage disposable load was bound to decline. In his paper he had elaborated the structural reasons for this decline. There were other, independent, reasons, such as the coning angle.

Major Cordes doubted the ability of rotors to reach maximum lift without collapsing through overconing. In the Air Horse all the blades must be stalled before a coning angle of 16° was reached, which he would agree was not "overconing."

Perhaps the best comment on the jet helicopters suggested by Mr. Britland was: give them the jets and they would finish the job. He thought that in fixed-wing aircraft the merits of jet propulsion for civil use

were often over-boosted because they were comparing hypothetical, and therefore somewhat ideal machines with real aircraft already operating (not merely flying). In helicopters both torque and jet-driven machines were *operationally* hypothetical and comparison did not look so good for the jet-driven rotor, which was only attractive in a narrow range of duties.

The *convertible* machine on the other hand was, as Mr. Anderson asserted, a great attraction. From the civil angle it might be premature but it was not too early to start development on a *compound* machine, deriving some lift from wings. It was one of the major attractions of the Air Horse that it was eminently suitable for such development. It might be just a little too early to disclose more at this juncture, but the helicopter was going ahead and those interested should not compare 1945 helicopters with 1955 fixed-wing machines.

THE EFFECT OF AERATION OF THE OIL ON THE BEHAVIOUR OF AN ENGINE LUBRICATING SYSTEM UNDER HIGH ALTITUDE CONDITIONS

by

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INTRODUCTION.

THE work described in this paper was done during the war, at the suggestion of the aircraft engine firms, as a result of difficulties with lubricating oil systems at high altitudes. Failure of oil pressure, seizure of bearings, or excessive loss of oil sometimes occurred and these defects were attributed to air in the lubricating oil, this air being greatly increased in volume at high altitudes because of reduced atmospheric pressure.

The behaviour of air-oil mixtures therefore was studied to obtain fundamental information which could be applied to engine lubrication at high altitudes. The present paper deals with that part of the research which was done on a complete lubrication system under simulated altitude conditions.

CAUSES OF AERATION.

In a typical dry-sump lubrication system the oil in the sump is considerably agitated and consequently increased in volume by aeration. To prevent the oil level building up in the sump, the scavenge pump must be of greater capacity than the pressure pump. The total excess capacity may be very high; for example, an in-line engine may have a scavenge pump at either end, each of which alone must be sufficient to keep the sump drained to prevent accumulation of oil when diving or climbing; the excess capacity then exceeds 100 per cent.

Air is therefore drawn into the pumps, thoroughly mixed with the oil and delivered to the scavenge line. Some of this air will dissolve in the oil in the earlier part of the scavenge line where pressures are high, and will be released from solution as small bubbles during the subsequent drop of pressure through the cooler. Thus an intimate mixture of air and oil is delivered to the oil tank. Most of the air separates in the tank, forming froth,* and returns to the sump through the tank vent pipe. Many fine bubbles are unavoidably carried through to the pressure pump, particularly if the oil flows rapidly through the tank, as when a partial circulator or "hot pot" is fitted.

Thus the excess capacity of the scavenge pump is the major cause of aeration, but retention of air in the oil is caused by the short time the oil stays in the tank. Froth can form by release of air bubbles either in the tank or in the crankcase; in the latter, it is assisted by the churning action of the moving parts of the engine.

Paper received June 1948.

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* "Froth" has been used to denote the mixture floating on the oil, and consists of air bubbles separated by membranes of oil; it is often called "foam." "Aerated oil" has been used to denote oil containing air bubbles in suspension. Oil containing only dissolved air has not been called aerated.

Effects of aeration.

Air in the suction line reduces pressure pump delivery—directly, by displacement of oil, and indirectly, by reduction of pump efficiency, because of expansion of air in the tooth clearance spaces. Any serious decrease of flow is accompanied by a rapid drop or intermittent fluctuations of pressure.

The formation of froth also may be a serious disadvantage. If the tank is vented directly to atmosphere, oil may be lost through the vent. If, as is more usual, the tank is vented to the crankcase, oil loss by frothing may still occur from the crankcase breather.

Both oil loss by frothing and reduction of pressure pump delivery normally occur only at high altitude, but in a few instances serious crankcase frothing has been reported at ground level, and its occurrence in vehicles such as tanks shows that it is not only an altitude problem.

Aeration has also been blamed for bearing failures, which have been variously attributed to local breakdown of the oil film, insufficient cooling, or failure of oil pressure. Aeration may be a serious problem when the engine oil is used for the hydraulic operation of devices such as governors and variable-pitch propellers, since the compressibility of the aerated oil is liable to cause hunting. Another possible ill effect of aeration is due to a mixture of air and oil having a lower specific heat than oil alone, and it has been stated[1] that this reduces the efficiency of the oil cooler.

Published work.

When this investigation began, little experimental work had been done on the subject. Since 1942 a few reports of American origin have appeared.[1–8] Many British aircraft firms are also known to have carried out experimental work on this subject, but so far no results have been made public. The only relevant publication is a short discussion by Campbell.[9]

It is not proposed to discuss these reports in detail, but, in general, they differ from the investigation described in the present paper in two respects; in the first place, in very few cases have reliable measurements of aeration been made, and secondly, either the effects of dissolved air have been ignored or else incorrect assumptions have been made about its behaviour.

Both Pigott[3] and Weeks[7] describe comprehensive investigations of aircraft lubrication systems in which the aeration is actually measured by an aeration meter, which is more fully described by Walsh and Peterson.[10] Their discussions of the results make no mention of dissolved air and its effects.

Schweitzer[4] derives a theoretical expression for the attainable altitude of an aircraft which takes dissolved air into account, but he assumes the oil to be saturated with air, an assumption which, it will be seen later, is often far from the truth. He also describes a by-pass type of aeration meter, but the authors' experience of this type showed it to be subject to large errors in certain circumstances. Campbell[9] also takes dissolved air into account qualitatively in his discussion, and his conclusions are largely confirmed by the present work.

The authors are encouraged to publish their own results by the belief that no previously published work gives so complete a picture of the behaviour of air in a lubrication system at altitude, particularly with regard to its entering into, and coming out of, solution.

THE MEASUREMENT OF AERATION.

The problem of measuring aeration.

If the circuit is not a closed one, it is possible to collect the aerated oil at the outlet from the system and measure the proportions of air and oil in any convenient manner. The measurement of the amount of air present in the oil in an existing closed circuit is far more difficult, as collecting the whole of the oil for a certain time would mean an interruption of the flow, which is not permissible. It is essential to be able to measure the aeration at different parts of the system without interfering with the conditions of flow.

In these circumstances, the aerated oil must be sampled without interrupting the main flow. Two problems are thus involved, that of collecting a representative sample, and that of determining the amounts of air and oil in this sample. Of these two problems, that of obtaining a true sample was found to be by far the more difficult.

A further problem is that of dissolved air. An aeration meter will measure free air (*i.e.* air in the form of bubbles) if it measures the air in the sample under the pressure prevailing in the pipe through which the oil is

flowing, but if the sample is allowed to attain atmospheric pressure before measurement, some dissolved air will come out of solution and will be measured also. An ideal aeration meter would measure both free and dissolved air separately.

The behaviour of dissolved air.

A search of published information on the solubility of air in oil showed that it obeys Henry's Law with sufficient accuracy for practical purposes, *i.e.*, the solubility, measured as a volume ratio at N.T.P.,* is directly proportional to the absolute pressure. The effect of temperature on solubility is relatively small.

Published values of the solubility of air in various oils lie between five and 15 per cent., with an average value of about nine per cent. Measurements made on the oil used in these tests (D.T.D. 109—summer grade) gave a value of 8.5 per cent.

It must not be assumed that, at every part of a circuit, the oil is saturated with air. Not only must the solubility be known but also the factors which influence the rates at which air dissolves in the oil and comes out of solution again. All the evidence available shows that both these rates are normally slow when the oil is still. Agitating the oil, increasing the surface area, or decreasing the depth increases both rates. In addition, the rate of release can be increased greatly by a sudden reduction of pressure; it is claimed, in fact[11], that this brings all the excess air out of solution, leaving the oil just saturated. The behaviour of air in the system depends more on these factors than on the pressure changes around the circuit.

The oil can be either unsaturated or supersaturated according to the circumstances, and is probably seldom just saturated. It is thus impossible to predict with any certainty the degree of saturation at any point; this can only be determined by measurement.

Preliminary attempts at measuring aeration.

The simplest method of sampling is by means of a small branch pipe, but it is unlikely that a sample so obtained will be representative; tests showed that there was a tendency for the air to segregate in one part of the cross section.

A method which appeared more promising was to use a meter in a by-pass to the main pipe, so that the total flow could be passed through either the main pipe or the meter, by means of inter-connected cocks. It was found that the aeration measured in this way was often much less than the true value, as found by collection and volumetric measurement of air and oil. Calculation showed that dissolved air could only account for part of the error, and the discrepancy was eventually found to be caused by air bubbles travelling faster than the oil. Under these circumstances, the ratio of air to oil by volume in any given length of pipe is less than the ratio of the volumetric rates of flow of air and oil.

Instead of taking a sample, it may be possible to measure some physical property of the oil which varies considerably with the amount of air. The properties most suitable are density, dielectric constant, and transparency. The first and last of these were used for experimental aeration meters, but little time was spent on meters of this type after it was realised that they must all be subject to the limitation that differences between the mean velocities of air and oil will affect the composition of the mixture in the meter.

The displacement aeration meter.

The meter finally designed* can be considered as a by-pass meter, in which the by-pass pipe is in the form of a lagged cylinder three in. diameter and 24 in. long, fitted with a piston. The mixture entering the lower end of the cylinder pushes the piston upwards and expels the fluid above it. The meter thus collects the whole flow during a short interval, but no cessation of flow is involved because the piston displaces fresh fluid into the circuit to replace that collected.

Figure 1 shows a diagrammatic sketch of the meter. Oil enters at A, and normally passes through pipe B and leaves at C. When a sample is being taken, this path is closed, and the oil flows into the cylinder, pushing up the piston and displacing the oil above it through pipe D to outlet C again.

The direction taken by the oil is determined by the three-way quick-acting valve E. This is a double-faced poppet valve, which is moved rapidly from one of its two seats to the other by means of strong springs. The

* Normal Temperature and Pressure.

* British Patent No. 571,692.

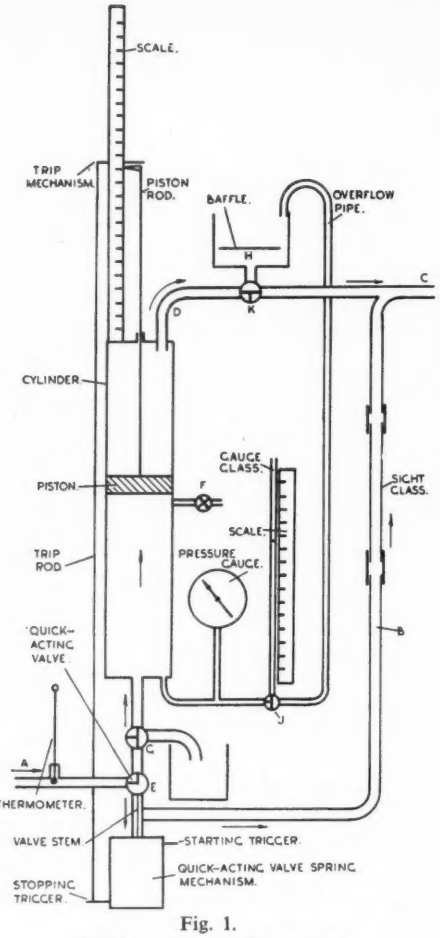

Fig. 1.
Displacement aeration meter.

springs have first to be "set," and are then released by a starting trigger. The piston rises until the top of the piston rod strikes a trip mechanism, which returns the valve to its upper seat; the oil now flows through pipe B again, leaving the sample below the piston. The pressure gauge is read at once, and also the volume of the sample, shown on the scale by a pointer on the piston rod. The latter reading gives the volume of oil and free air, under pressure. The cock K is then turned to release the pressure suddenly in the upper part of the cylinder. The expansion of the air in the sample and the release of dissolved air push the piston upwards and excess oil above the piston is ejected into tank H. Before reading the new volume, cock J is turned to connect the gauge glass, which contains air-free oil, to the cylinder. The cock F is now opened, and a thermometer or thermocouple is inserted to measure the temperature of the air.

The second reading on the scale above the cylinder gives the volume of oil, free air, and air which has come out of solution due to reduction of pressure to atmospheric. The gauge glass reading gives the volume of oil. After suitable corrections for temperature and pressure have been applied, the degree of aeration of the oil, and the proportions of the total air in the free and dissolved conditions, can be calculated.

The meter is also used to measure the rate of flow by recording automatically the time during which valve E is open. This meter is suitable for all oil temperatures and positive pressures within the range used in an engine, but not for pressures below atmospheric.

THE BEHAVIOUR OF A TYPICAL LUBRICATING SYSTEM UNDER SIMULATED HIGH ALTITUDE CONDITIONS.

Description of circuit.

The main details of the test rig are shown in Fig. 2. The tank is of approximately 18-gallon oil capacity with a four-gallon air space, and is fitted with a "hot pot" and "swirl ring."

The sump, from a Rolls-Royce Merlin crankcase, has two scavenge pumps, one drawing oil directly from the rear well and the other through a pipe from the forward well. Each pump has 1.2 times the pressure pump capacity, giving a total excess capacity of 140 per cent. The scavenge and pressure pumps, which are all attached to the base of the rear sump well, were driven through gears by a variable-speed motor. The tank was normally connected by a horizontal straight pipe to the pressure pump inlet. In the high pressure line, a pressure-relief valve passed excess oil direct to the crankcase. The main flow passed through a restriction made by inserting a rod into the pipe; the pressure drop was caused by viscous drag between the oil and the walls of the long annular space. Adjustment of the pressure-relief valve and the length of restriction made it possible to obtain a relation between oil

pressure and pump speed similar to that of the engine. After passing through a gas heater, the oil was sprayed into the crankcase through holes in the sides of a pipe.

A similar viscous restriction was fitted in the scavenge line before the cooler. The flow through the cooler was controlled by a Clarke "viscosity valve," which by-passes the cooler until the viscosity has fallen to a predetermined value. As it was decided not to reproduce the increase and decrease of temperature around the circuit, on account of the very large quantity of heat which would have to be first supplied and then dissipated, the cooler was blanked off. Branch connections and by-passes were arranged to permit the use of the aeration meter in either the high pressure line or the scavenge line. The by-pass valves were adjusted to give the same pressure drop as the meter, so that no change occurred in operating conditions when the meter was used.

Lengths of glass tube were fitted to several pipes, and windows were fitted to the oil tank at the top and side. The whole circuit was closed to the atmosphere by a toughened glass cover plate over the sump, and connection was made from the latter to a vacuum pump through an oil trap. The tank was thus evacuated through the vent pipe, and to prevent collapse it was enclosed in a steel drum connected to the vacuum line and fitted with windows opposite those in the tank.

Test procedure

Tests were made under "steady" conditions, in which the circuit was maintained at each required pressure for long enough to reach stability before taking observations, and under conditions to represent "climbing," in which the pressure was reduced continuously at a rate corresponding to 2,200 or 4,400 ft. per min. vertical velocity.

Most tests included measurements of aeration and flow. This was not possible in the time available under climbing conditions, and tests were therefore generally made under "steady" conditions. In "climbing" tests, readings were confined to measurements of flow and the more important pressures round the circuit, and the meter was used only in the high pressure line. Oil pressures were set at conditions corresponding to ground level and no further adjustments were made throughout the test run.

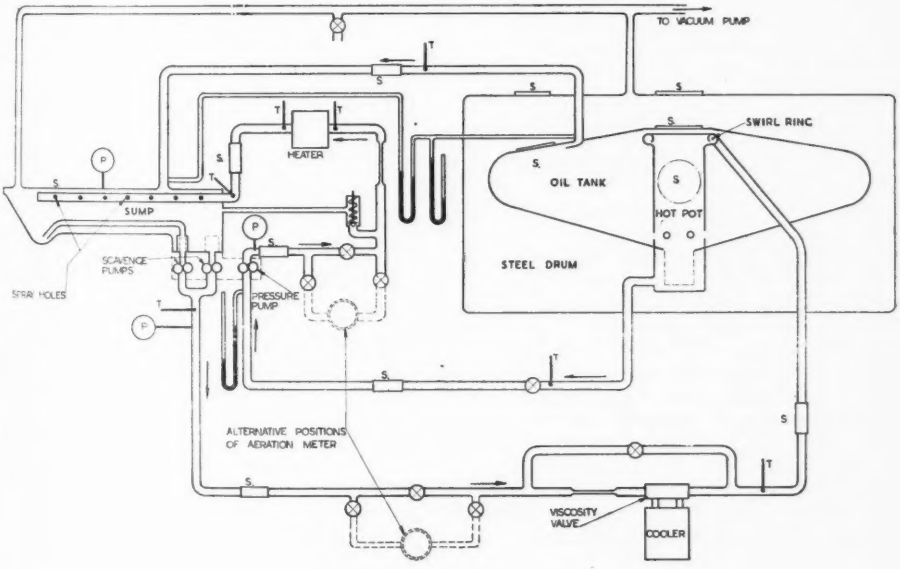

Fig. 2.
Diagrammatic layout of test rig.
P—pressure gauges. T—thermometers. S—sight glasses.

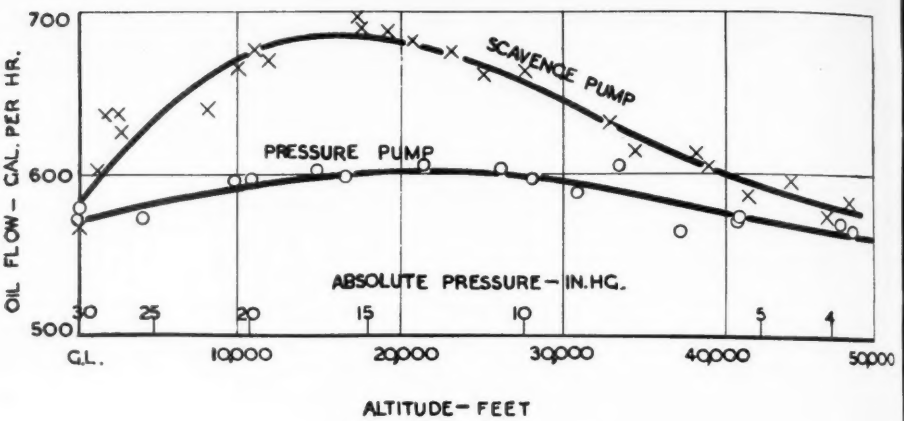

Fig. 3.
Oil flow under "normal conditions."

All observations have been plotted on a base representing the altitude corresponding to the absolute crankcase pressure. A scale of crankcase pressure has also been marked along this base. Aeration has been expressed as an air/oil ratio, by volume, at the pressure and temperature of the oil in the crankcase. The amounts of free and dissolved air plotted are those measured at the point in the pipeline where the sample was taken, and the dissolved air *includes* that normally present in the oil at atmospheric pressure (8.5 per cent.).

TESTS UNDER "NORMAL CONDITIONS."

The effect of altering any variable was judged by comparison with a test under "normal" conditions. In this test, the tank was filled to one inch below the "full" level, the amount of oil needed being about 16 gallons. The pump speed was 1,950 r.p.m. and the oil temperature 70°C. Valve restrictions in both lines were set initially to give 80 lb. per sq. in. main oil pressure and 50 lb. per sq. in. scavenge pressure, no further adjustment being made except when the effect of back pressure due to that particular restriction was the object of the investigation. In order that the relatively brief notes of test results made later may be clearly understood, the results of the tests under normal conditions are discussed in some detail.

(*a*) *Delivery of pumps.*

The quantities of oil flowing in the high pressure and scavenge lines are shown in Fig. 3. Judged by the small drop of pressure pump delivery this condition gives satisfactory operation at altitude. The scavenge pump delivery rises to 685 gal. per hr. at 16,000 ft. and falls again to 580 gal. per hr. at 47,000 ft.

(*b*) *Oil flow in vent pipe.*

The difference between pressure pump delivery and scavenge pump delivery is represented almost entirely by the flow of oil as froth along the vent pipe. This flow is plotted against altitude in Fig. 4, which also shows the pressure drop along the vent pipe. The similarity of these curves and visual observation support the high flow values, and a check measurement by direct collection and weighing showed close agreement.

This flow may result in crankcase frothing, but is apparently beneficial to the pressure pump, being always accompanied by increased delivery. This is probably due to the pressurising of the tank by the resistance to flow along the vent pipe, since the pump inlet pressure increased by about three in. mercury at 16,000 ft.

(*c*) *Scavenge pump failure.*

At high altitude froth built up in the sump, starting at the forward end, and it was assumed that partial failure had occurred at the forward scavenge pump, which has a long suction pipe. A more rapid fall in efficiency of the scavenge pumps than the pressure pump is to be expected, because of the less

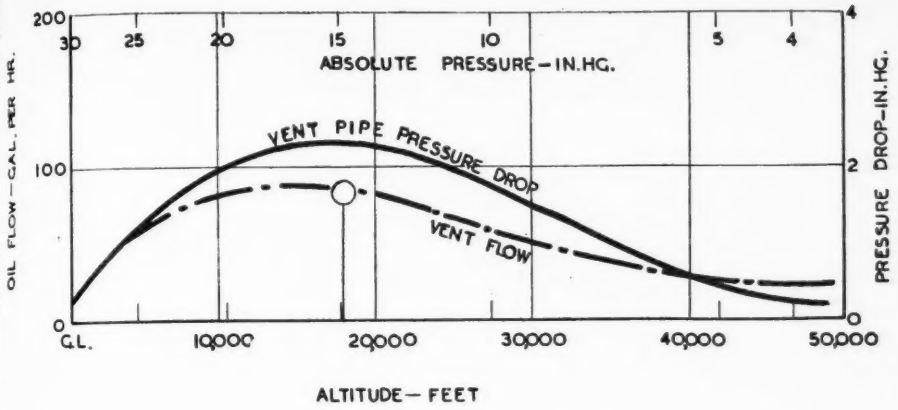

Fig. 4.
Flow in vent pipe under "normal conditions."
O Direct measurement of vent flow.

favourable conditions in the suction line of one of the scavenge pumps.

(d) Aeration.

The influence of altitude on aeration in the high pressure and scavenge lines is shown in Figs. 5 and 6 respectively. The curves are typical of most of the tests, and the following discussion is therefore generally applicable.

An error might be introduced by the meter's inability to record the true volume of air if it is less than that required to saturate the oil at one atmosphere. A line has been drawn on Figs. 5 and 6 showing the "lower limit of measurement by meter." Under all conditions tested, the total aeration curve was sufficiently above this line to make such an error unlikely.

It should be noted that the ordinates of Figs. 5 and 6 show the air/oil ratios by volume at the altitude pressure, and do not directly represent volumes in the pipe under pressure. The present method of plotting has been chosen because the quantity of most interest is the volume of air at the pump *inlet*, which is very nearly at the altitude pressure; it is this volume of air which affects the pump delivery.

The total aeration must remain constant from the tank through the pressure pump to the crankcase, since air can only enter or leave the system either in the tank or in the crankcase. To find the quantity of free air at any point, it is necessary to draw on Fig. 5 a line showing the dissolved air at that point at different altitudes. The saturation air/oil ratio at any point where the pressure and temperature are known is readily calculated.

"Saturation lines" have been plotted on Fig. 5 showing this ratio at the pump inlet and at the pump outlet. If these lines really represented the dissolved air present, the volume of free air at the inlet side of the pump at high altitudes would be very large. Consideration of pump delivery, however, shows that the free air cannot be so large, leading to the conclusion that the oil at the pump inlet must be in a supersaturated condition. It is also interesting that, although the oil in the high pressure line is far from saturated, some free air is still present; this could be observed in the sight glass.

The aeration curves of Fig. 6 demonstrate the low efficiency of the scavenge pumps when supplied with highly aerated oil. The excess capacity of the combined scavenge pumps is 140 per cent. If the scavenge pump were as efficient as the pressure pump, therefore, the aeration would be about 1.4, whereas the total aeration over most of the altitude range, including dissolved air, is only about 0.8.

These curves also differ in general shape from those of Fig. 5. It is suggested that the fundamental shape is similar, but that at those altitudes at which froth is flowing along the vent pipe the increased froth in the sump makes the scavenge pumps work more efficiently; they draw in more air when it is

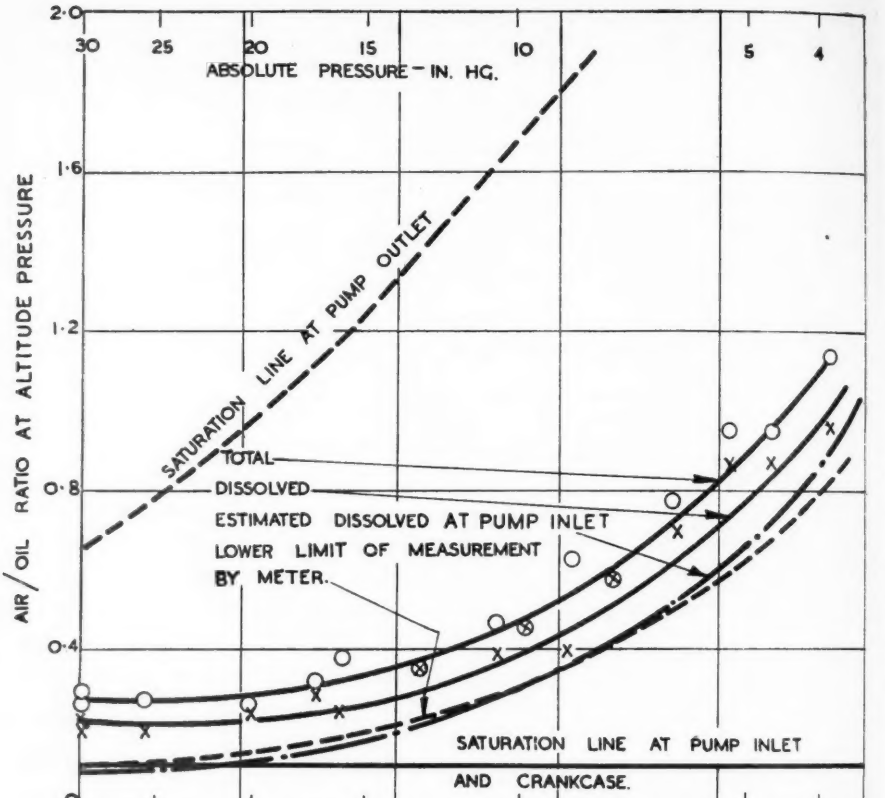

Fig. 5.
High pressure line aeration under "normal conditions."

mixed with the oil than when the oil and air are separate. This suggestion is in agreement with the observation that under conditions in which vent flow was suppressed, the aeration curves for the scavenge line were nearly always similar to those for the pressure line (see, for example, Fig. 12).

The saturation curves for the crankcase and the scavenge pump outlet have been plotted as in Fig. 5. At the pump outlet, even with a large amount of free air present, the oil is not saturated. If, at any altitude, the total aeration in the high pressure line is multiplied by the ratio of the main oil flow to the scavenge oil flow, the total air quantity in the high pressure line as a proportion of scavenge oil flow may be plotted as in Fig. 6. The difference between this curve and the curve of total aeration in the scavenge line represents the air flow through the vent pipe. It will be observed that at high altitude this is almost negligible.

(*e*) *Supersaturation.*

If, at any given speed, the efficiency of the pressure pump is assumed to remain constant, the total volume of air and oil drawn in will always equal the volume of non-aerated oil which the pump would deliver. Taking the

true pump delivery at normal speed to be 685 gal. per hr. (the highest flow in tests in which the oil appeared to have no air bubbles, see Fig. 14), the volume of free air entering the pump every hour is given by the difference between 685 and the observed oil delivery. Subtracting this from the total aeration gives the estimated dissolved air at the pressure pump inlet (see Fig. 5). Above about 10,000 ft., this exceeds the saturation quantity of air, the excess becoming very large at high altitudes. Under altitude conditions, therefore, a considerable volume of air remains in the oil in the tank and suction line in supersaturated solution.

This curve of dissolved air at pump inlet also gives a lower limit for the dissolved air at the end of the scavenge line, and has therefore been reproduced in Fig. 6. The difference between this curve and that showing the dissolved air at scavenge pump outlet represents the maximum quantity of air which could have come out of solution in the scavenge circuit. Above 40,000 ft., hardly any air appears to be released from solution. This also agrees with sight glass observations.

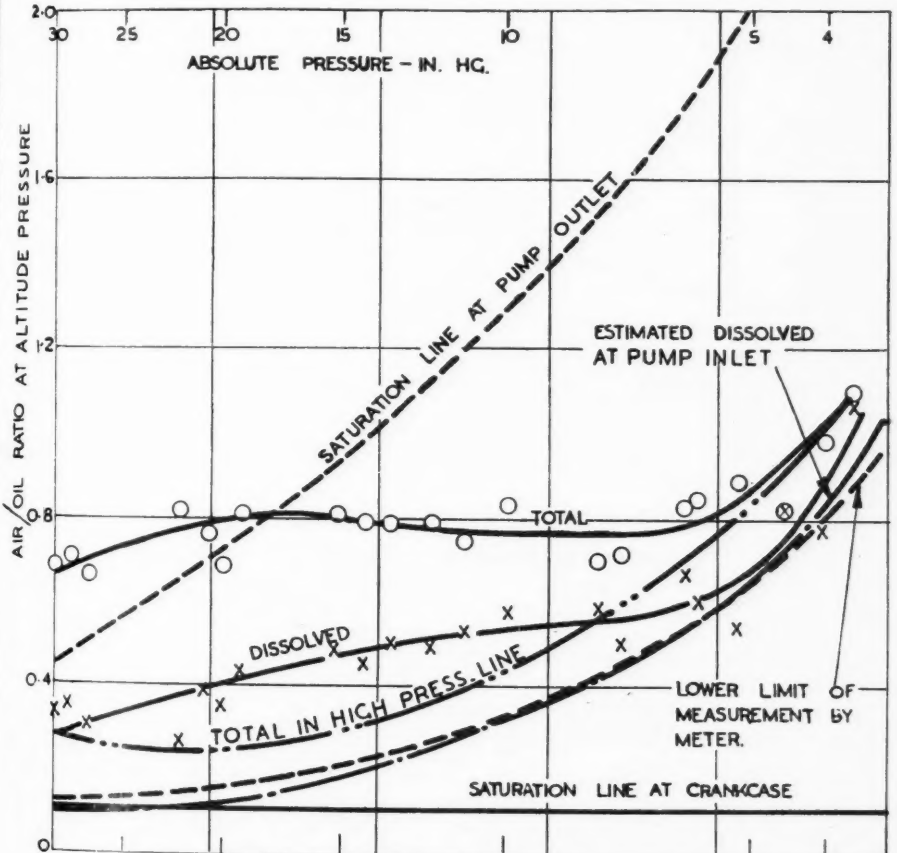

Fig. 6.
Scavenge line aeration under "normal conditions."

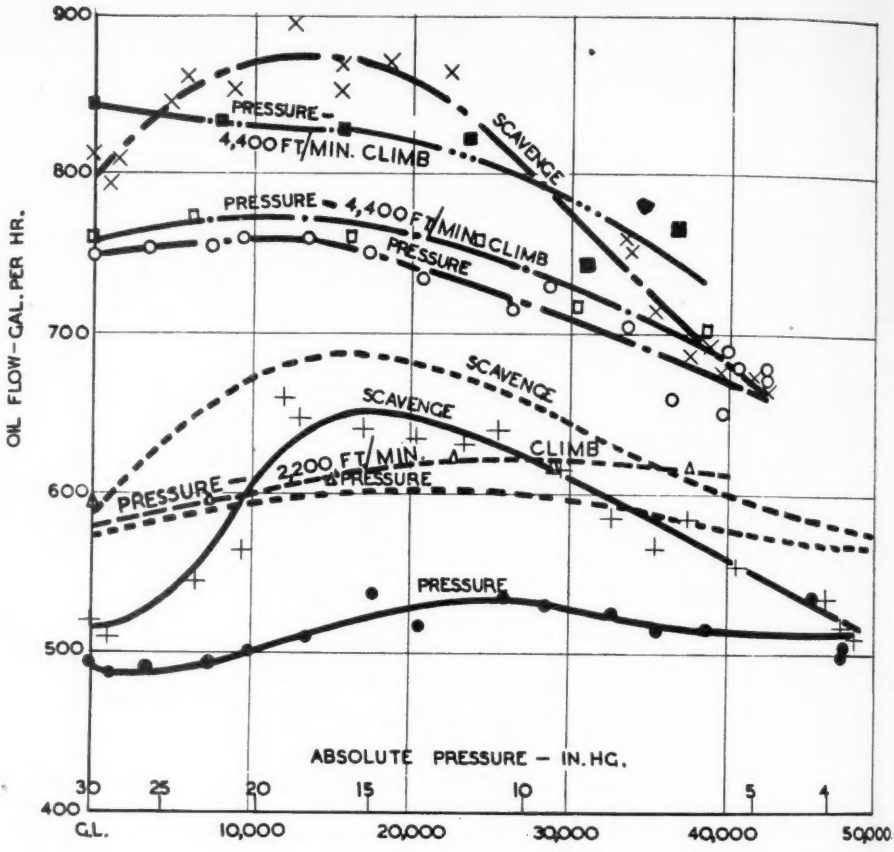

Fig. 7.

Effect of pump speed on oil flow.

——————— Pump speed 1,650 r.p.m.
- - - - - - - - - - - - - - - - - Pump speed 1,950 r.p.m.
——— — ——— Pump speed 2,500 r.p.m.
——— . . . ——— Pump speed 2,900 r.p.m.

EFFECT OF OPERATING CONDITIONS.

(*a*) *Effect of pump speed.*

The reduction of pressure pump delivery with increase of altitude is more pronounced the higher the speed, as shown in Fig. 7.

Both the total aeration in the scavenge line and the proportion of dissolved air were found to increase with pump speed. The "load" on the tank considered as a separator thus increases with speed on account of greater aeration as well as greater flow. The effect is to increase the aeration in the suction line as the speed is raised; this was shown by an increase in total aeration in the high pressure line at ground level, from 15 per cent. below normal at 1,650 r.p.m. to 15 per cent. above normal at 2,500 r.p.m. Finally, the reduced efficiency of the pressure pump and the increased aeration in the oil delivered to the crankcase both tend to increase the air in the scavenge line.

Even at the highest speed, there was no sign of instability or pump failure.

(*b*) *Effect of rate of climb.*

Figure 7 shows a small increase of flow when climbing, especially at high altitudes. Corresponding to this, there was an increased pressure drop and increased oil flow along the vent pipe. This is because, when climbing rapidly, no time is available for air to come out of solution and for the consequent froth to be dispersed before high altitudes are reached.

(*c*) *Effect of oil temperature.*

Pump delivery decreased with reduction of temperature (Fig. 8) and at 65°C. an appreciable drop of delivery accompanied increase of altitude. This is caused partly by more air being carried through the tank, as was shown by measurements of increased aeration in the high pressure line, and partly by a larger pressure drop in the suction pipe, leading to a very low pump inlet pressure at altitude. At 120°C., on the other hand, there was no free air in the high pressure line.

The change of scavenge line aeration with temperature is more complex, the shape of the aeration curves being affected more than the degree of aeration. At 65°C. the usual "hump" had disappeared, corresponding to the small vent flow shown in Fig. 8.

The vent flow was found to be smaller at 120°C. than at 90°C. in agreement with the results of a separate investigation which

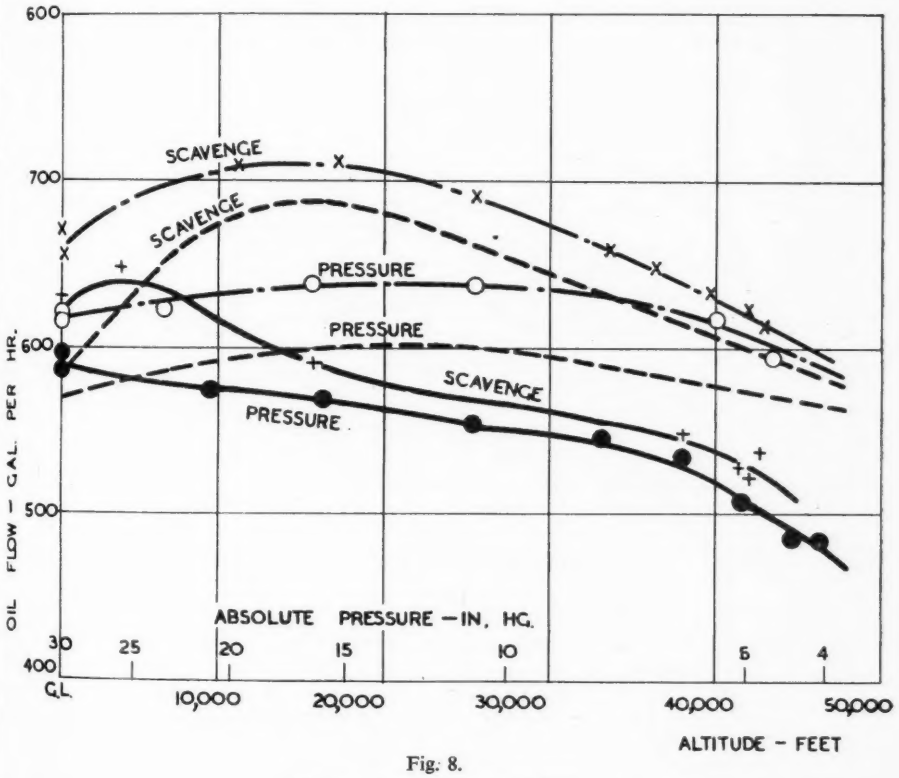

Fig. 8.

Effect of temperature on oil flow.

———— Oil temperature 65°C.

- - - - - - - - - - - - - - - - Oil temperature 90°C.

———— — ———— Oil temperature 120°C.

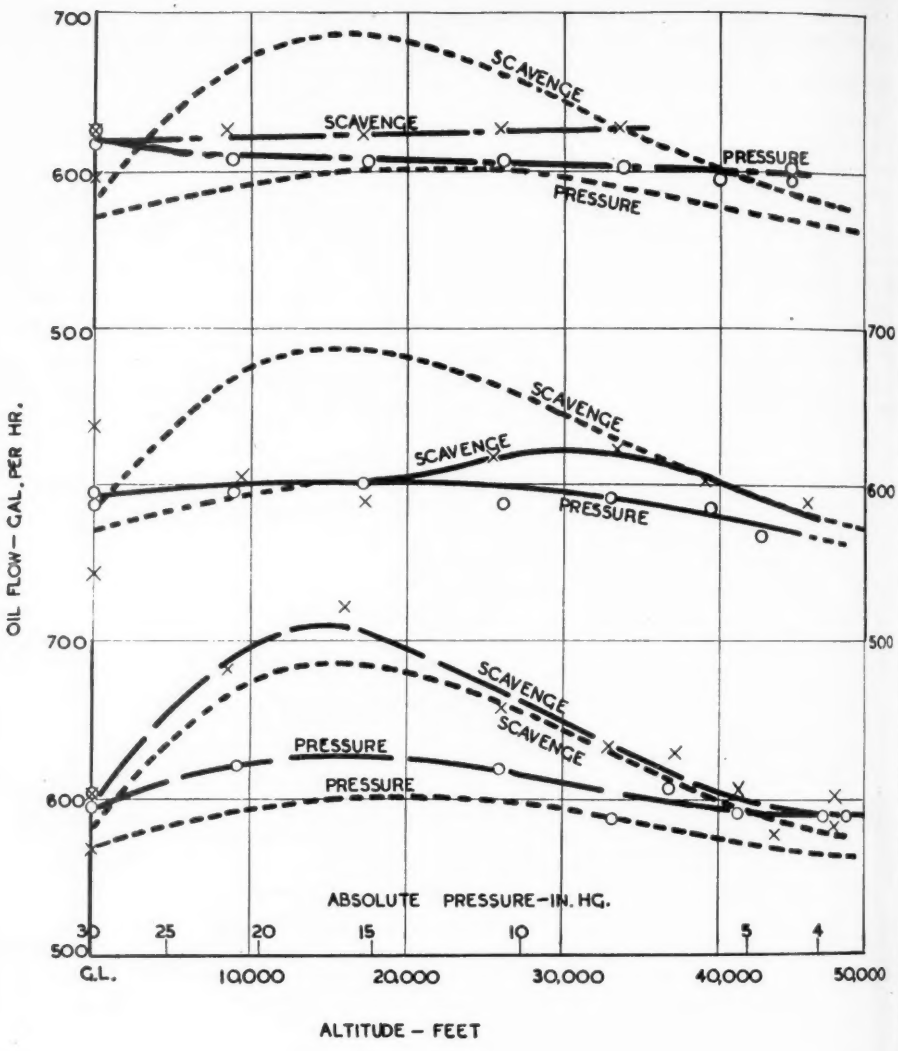

Fig. 9.

Effect of scavenge back pressure on oil flow.

———— — ————Scavenge pressure 20 lb. per sq. in. (without cooler)

————————Scavenge pressure 50 lb. per sq. in. (without cooler)

----------Scavenge pressure 50 lb. per sq. in. (with cooler)

———— ————Scavenge pressure 70 lb. per sq. in. (with cooler)

showed reduced froth stability at higher temperatures. The vent flow was reduced also at 65°C., probably because of the greater time required for the release of dissolved air. More air is then carried through the tank, and some of this is released in the suction line, with detrimental effect on the performance of the pump, as already noted.

(*d*) *Effect of oil level in tank.*

A reduction of oil level by 1½ in., corresponding to three gallons less oil, reduced vent pipe flow, as would be expected. Pressure pump delivery was reduced by about five per cent.

(*e*) *Effect of main oil pressure.*

Pressure pump delivery was independent of pressure up to 100 lb. per sq. in., but increased pressure was accompanied by a reduction of vent flow at altitudes below 25,000 ft. The small changes of aeration and flow observed were insufficient to indicate the cause of this change. There was no free air in the high pressure line at 100 lb. per sq. in.

(*f*) *Effect of scavenge back pressure and type of restriction.*

Four tests were made:—

1. Back pressure 50 lb. per sq. in. by cooler and restriction;
2. Back pressure 20 lb. per sq. in, bypassing cooler and restriction;
3. Back pressure 50 lb. per sq. in., by increased restriction with cooler bypassed;
4. Back pressure 70 lb. per sq. in. by cooler and increased restriction.

Figure 9 compares the pump deliveries under these conditions.

In test (2) the dissolved air in the scavenge line was found to be reduced and the mixing effect of the passages in the cooler was removed. Both these changes should improve separation of air in the tank by reducing the number of fine bubbles. Reduced vent flow and improved pressure pump delivery would therefore be expected; the results confirmed this.

In test (3), the aeration was unchanged as compared with "normal" conditions, but vent flow was almost eliminated. The mixing effect of the cooler thus appears to be a major factor affecting tank frothing.

Increasing scavenge back pressure, test (4), gave about four per cent. increase of pressure pump delivery at all altitudes. There was more dissolved air in the high pressure line, but no increase of total aeration. An increased proportion of dissolved air in the scavenge line was also measured— a natural result of a higher pressure. The increased pump delivery is attributed to an increased tank pressure of about ½ in. of mercury, but the cause of this is not clear, since no change of vent flow was recorded.

(*g*) *Effect of suction line restriction.*

Two tests were made with artificial restriction produced by a gate valve, the pressure drop at the pump inlet being 2½ and 16½ in. mercury respectively, at ground level. Fig. 10 shows the delivery of the pressure and scavenge pumps.

In view of the large pump inlet depression the drop in delivery caused by the maximum restriction was surprisingly small at ground level, but it was more pronounced at altitude. Violent fluctuations of pressure were encountered at 42,000 ft. at which altitude the absolute pump inlet pressure was one inch of mercury, which is equal to the centrifugal back pressure of the oil in the tooth spaces.

On account of the smaller quantity of oil supplied to the scavenge pump, the aeration in the scavenge line was increased. There was no appreciable change of vent flow or of high pressure line aeration, showing that the tank conditions were little changed. Evidently the increased scavenge line aeration is in the form of large bubbles which readily escape in the tank.

Artificial restriction of the suction line has sometimes been employed to simulate altitude conditions. These tests indicate the error involved in this procedure. For example, in Fig. 10, points A and B both represent pump deliveries with an absolute inlet pressure of 13.5 in. mercury; A was obtained by a restriction, and B by reduction of pressure of the whole system. The restricting valve, by expansion of free air and release of dissolved air, creates an artificially high ratio of free air to oil at the pump inlet.

(*h*) *Effect of tank level relative to pressure pump.*

The difference between lowering the whole tank and lowering the oil in the tank should be appreciated; lowering the oil level enlarges the space available for frothing as well as causing a reduction of pressure at the pump inlet.

Lowering the tank by one foot reduced the pressure pump delivery throughout the range. It is interesting to note that a pressure corresponding to an altitude of 60,000 ft. could be reached without excessive frothing in the sump. Neither pressure nor scavenge

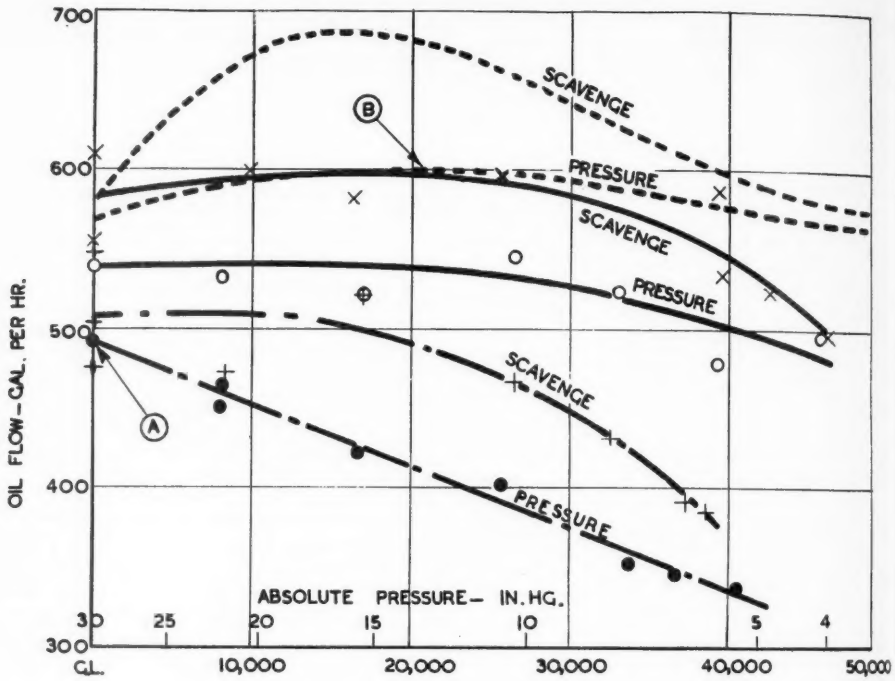

Fig. 10.

Effect of suction line restriction on oil flow.

----------Normal good suction line.

——————————Pump inlet depression 2½ in. mercury at ground level.

——— — ———Pump inlet depression 16½ in. mercury at ground level.

pumps showed any signs of failure, although the pressure pump delivery fell to 470 gal. per hr. Satisfactory scavenging at this altitude was apparently made possible by the reduced pressure pump performance.

Below 25,000 ft., the vent flow was reduced, leading to a corresponding pressure reduction at the pressure pump inlet and reduction in scavenge line aeration. The high pressure line aeration was lower at all altitudes.

Discussion of results.

(*a*) *Conditions in the oil tank.*

It is important to secure the greatest possible degree of separation in the tank. It has been seen (Fig. 5) that at ground level the oil leaving the tank is saturated with dissolved air and, in addition, contains about 0.2 of its volume of free air. Above 10,000 ft. this oil becomes increasingly supersaturated, but there is little increase in the amount of free air.

Aeration at the tank outlet can be judged by the pressure pump delivery and the aeration in the high pressure line. Increasing the scavenge back pressure leads to more dissolved air, but this appears to remain in solution throughout the circuit. The free aeration of the oil leaving the tank is diminished by removing the cooler or by raising the oil temperature, but increasing the pump speed leads to greater aeration.

Air which separates in the tank forms froth on the surface. When there is a space above

this froth, air alone flows along the vent pipe, but if the froth rises to the roof of the tank, the air flowing along the vent pipe carries considerable quantities of oil. This may sometimes increase oil loss through the crankcase breather, but in the present system the oil is returned by the scavenge pump, which then pumps a greater volume of both air and oil.

Under normal conditions, oil flow through the vent is only appreciable at moderate altitudes (Fig. 4), but under climbing conditions it is still present at high altitudes. Oil flow through the vent pipe decreases with increasing delivery pressure of the pressure pump. Scavenge back pressure in itself appears to have little influence on vent flow, but removal of the cooler eliminates it (Fig. 9); dissolved air in the scavenge line is apparently carried through the tank, but free air is mainly released and, if it has been well mixed with oil in the cooler, forms sufficient froth to produce vent flow. A lower oil level gives greater space for frothing before vent flow begins. The effect of temperature is more complex (Fig. 8) and it has been suggested that increased temperature has two opposing effects: a reduction of froth stability, and an increase in the rate at which air is released from solution. The net result is that the vent flow is greatest at an intermediate temperature.

(*b*) *Pressure pump delivery.*

The delivery of the pressure pump depends on its speed and the free aeration at the pump inlet. The latter depends on the aeration at the tank outlet and the pressure drop along the suction line. The factors affecting the mixture leaving the tank have already been discussed, and in this test rig the pressure drop in the suction line was normally small. With oil at 65°C. this pressure drop was three to four inches of mercury. Under these conditions, air bubbles expand and dissolved air is released from solution, especially at high altitudes where the pressure ratio between the ends of the pipe is large. Although the delivery was reduced, failure of the pressure pump did not occur because the attainable altitude, even under these conditions, was still determined by the scavenge pump. With a restriction in the suction line, the pressure pump reached its attainable altitude at 42,000 ft.

Apart from these two instances, the pump inlet pressure is nearly equal to the altitude pressure augmented by the pressure caused by oil flow through the vent pipe. This vent flow is beneficial to the pressure pump, and the greatest delivery will be obtained with a low aeration at the tank outlet and a high vent flow. The most favourable operating conditions appear to be high oil temperature, low pump speed, and as little resistance to flow as possible in both suction line and scavenge line.

(*c*) *Failure of the scavenging system.*

The low volumetric efficiency of the scavenge pumps is generally an advantage, as it reduces the amount of air delivered to the tank. It has been shown that scavenge line aeration is dependent on the oil flow through the vent (Fig. 6), and it has been suggested that this is because of the increased efficiency of the pumps when their inlets are immersed in froth, instead of being partly covered by oil with air above its surface. This increased efficiency automatically keeps down the sump level until an altitude is reached (47,000 ft. in this rig) at which the absolute pressure at one scavenge pump inlet is insufficient to fill this pump. The level in the sump then builds up rapidly. In some systems, the pressure pump may fail first, depending on the design of pressure and scavenge pumps and their inlet passages. In systems where scavenge pump failure is the criterion of attainable altitude, higher altitudes may be reached with a low efficiency of the pressure pump which avoids overloading the scavenge system.

Improvement of the scavenge system can be effected by better design, but not by changes of operating conditions, since vent flow always ceases at high altitudes, and therefore cannot affect scavenge pump performance.

METHODS OF IMPROVING PUMP DELIVERY.

Although aeration originates in the sump, it only becomes detrimental if free air is still present at the pressure pump inlet. Corrective measures therefore can be applied anywhere between these two points. Such measures include: prevention of entry of air into the scavenge pump; removal of air, in the scavenge line or the tank; prevention of the formation of fine bubbles, by minimising the breaking up of bubbles, and by reducing dissolved air or keeping it in solution; and increasing pump inlet pressure.

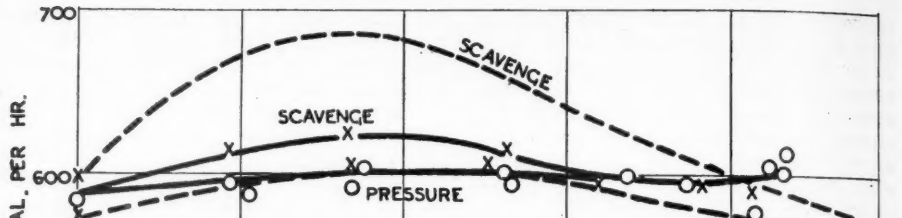

Fig. 11.
Effect of tank pressurisation on oil flow.
---------- Without pressurising valve.
———————— With pressurising valve.

Tests were made on a few of the many possible methods of improvement. It should be emphasised that these tests were only exploratory, no attempt being made to find the conditions under which any particular modification would give its most favourable results.

TANK PRESSURISATION.

A high tank mounting and a low-resistance suction line are the aim of the installation designer, but if these are not possible, a "pressurising" valve in the tank air vent has sometimes been found to improve altitude performance. On the present rig, a spring-loaded valve was employed, opening nominally at 2½ lb. per sq. in.

Figure 11 shows an increase of oil flow, except between 15,000 and 30,000 ft. More noticeable than this is the considerable reduction of oil flow through the vent. Under climbing conditions, the pressure pump delivery was reduced with the normal tank position but in a test with a low tank position there was a slight increase. These tests show that tank pressurisation is only likely to be helpful if the suction line is of poor design. Free air in the high pressure line was reduced at high altitude, being too small to record above 30,000 ft. The dissolved air was increased at all altitudes, but the total aeration was only increased below 30,000 ft. In the scavenge line the dissolved air was unchanged, but the total aeration was increased between 10,000 and 40,000 ft.

The explanation of the effects of pressurisation is not altogether clear, but the following discussion may help towards an understanding. Tank pressurisation has two opposing effects; the pressure in the suction line is increased, but the air separation in the tank is reduced. At high altitudes, the amount of air separated in the tank is small even without the pressurising valve, and the beneficial effect of increased suction line pressure is then the major factor. Under climbing conditions air separation is normally great, and the effect of the valve in suppressing this evidently outweighs any advantages of higher pressure in the suction line.

In interpreting the results, it must be remembered that although the scavenge oil is more aerated, the scavenge line oil flow is reduced, so that the rate of delivery of air to the tank is practically unchanged by pressurisation. Thus the total aeration in the suction line depends only on the separation in the tank.

Pressurisation by flow of oil through the vent has been suggested earlier as the reason for the increased pressure pump delivery accompanying this flow. The increase is large compared with the small degree of pressurisation produced in this way. But pressurisation by vent flow is a result of separation of air, while if the tank is pressurised by a valve, the pressure is applied before any separation takes place. Greater separation and better pump performance will thus be expected if the pressure is due to

vent flow, than if the same pressure is applied by external means.

De-aerator in scavenge line.

A bleed hole $\frac{1}{8}$ in. diameter was made in the top of the pipe at the end of a horizontal pipe four ft. long immediately following the scavenge pump. Experiments had shown that this device, when it can be applied, is as efficient as many de-aerators of more complicated design. Oil loss through the bleed was about 10 per cent. of the total flow. Since it was difficult to connect the bleed to the tank, it was connected to the low pressure side of the cooler. It was considered that no appreciable re-mixing would occur in the short pipe between this point and the tank.

As a de-aerator, the design was satisfactory; Fig. 12 shows the reduction of aeration in the scavenge line. The reduction of dissolved air may have been influenced by the drop of pressure caused by flow through the air bleed.

Under normal steady conditions, the effect of the de-aerator on pump delivery was negligible above 10,000 ft. With the de-aerator the oil flow in the vent pipe was reduced and, to obtain a fair comparison with and without de-aeration, it was considered necessary to eliminate the effect of the tank pressurisation due to vent flow. Further tests were made therefore with the pressurising valve in position, the effect of vent flow then being of reduced significance. Under climbing conditions with a pressurising valve, the pump delivery above 30,000 ft. was increased by using the de-aerator.

Reduction of tank frothing is the main improvement gained by using a de-aerator. The de-aerator only removes free air and has little effect on pump delivery, since this air is mainly in the form of large bubbles easily separated in the tank. The fine bubbles formed by the release of dissolved air require more time to separate, and are therefore carried into the suction line, affecting the pump performance.

Injector in suction line.

To improve pump performance appreciably, pressurisation should be confined to the suction line, for example, by using a booster pump at the base of the tank. A simpler solution is the use of an injector inserted near the tank outlet and supplied with oil from the high pressure line. The

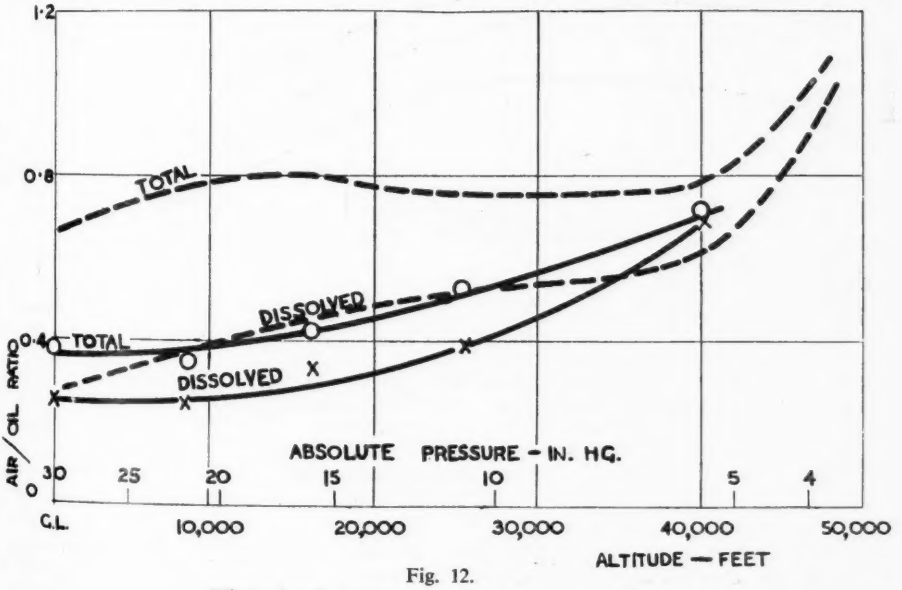

Fig. 12.
Effect of a de-aerator on aeration in scavenge line.
---------- Without de-aerator.
———————— With de-aerator.

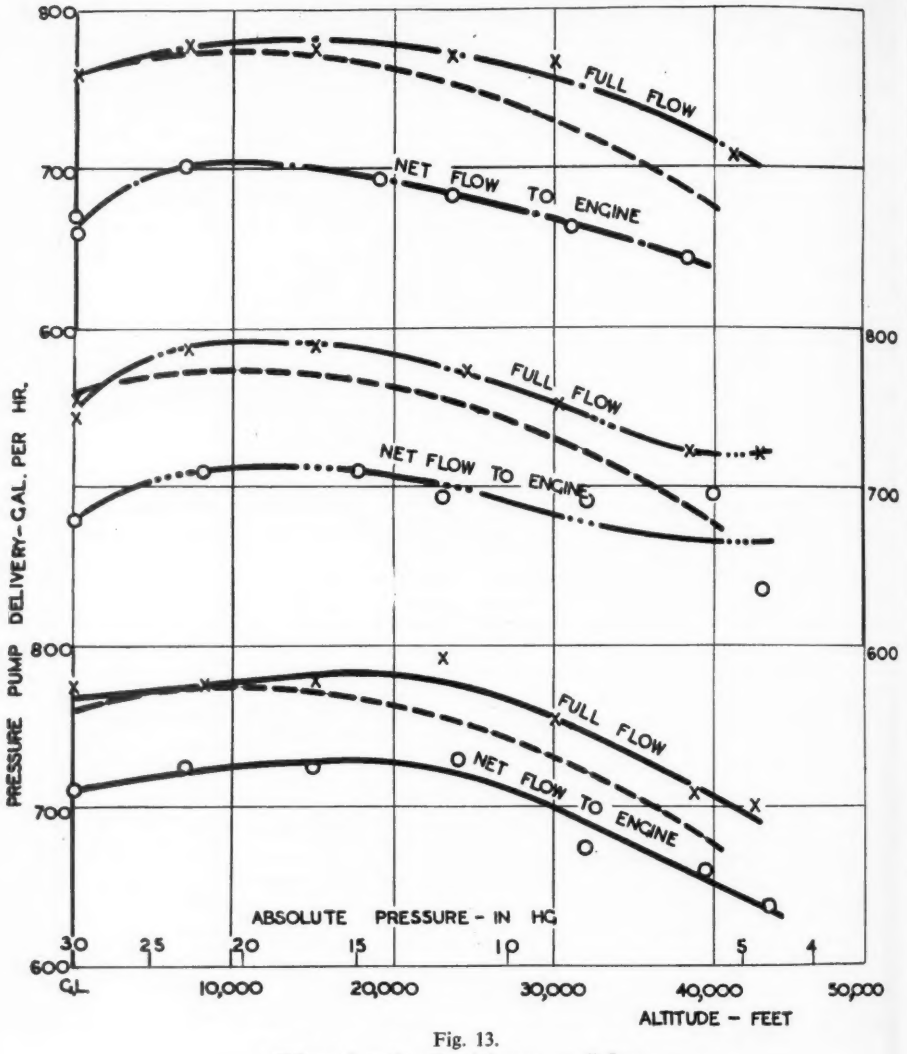

Fig. 13.

Effect of suction line injector on oil flow.

Pump speed 2,500 r.p.m. Rate of climb 4,400 ft. per min.

---------- Without injector.

———————— Injector with 15 lb. per sq. in. jet pressure.

———— . . . ———— Injector with 50 lb. per sq. in. jet pressure.

———— — — ———— Injector with 70 lb. per sq. in. jet pressure.

consequent reduction of oil supply to the engine at low altitudes would be justified if the method gave improved pump performance at high altitudes.

Tests were made with a three-stage injector, using a high pump speed under climbing conditions. The injector was fitted just outside the vacuum chamber, about three feet from the tank itself, and the pressure at the injector jet was varied from

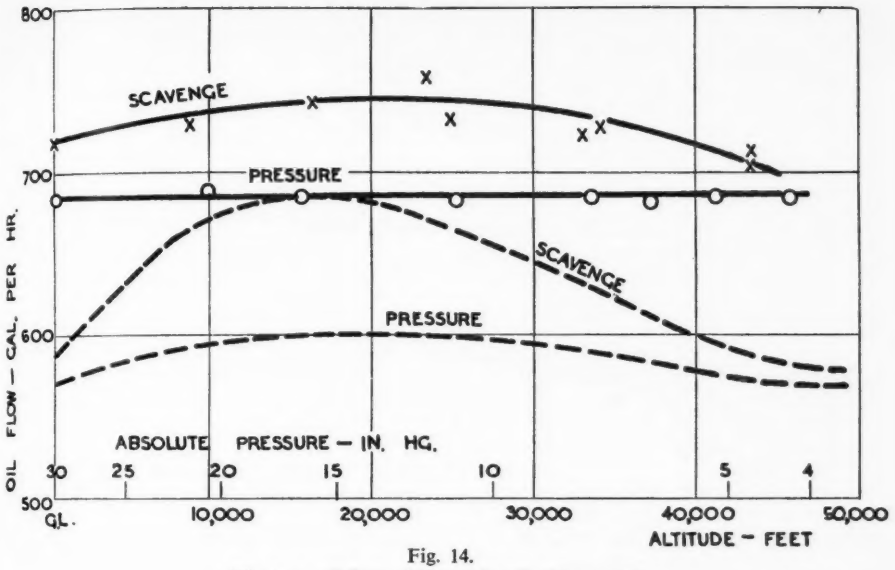

Fig. 14.
Effect on oil flow of by-passing the "hot pot."
---------- "Hot pot" in circuit.
———————— "Hot pot" by-passed.

15 to 70 lb. per sq. in. With the highest jet pressure, the increase of pump inlet pressure was 1.3 in. of mercury at ground level.

With all jet pressures, some increase of total pump delivery was achieved, as shown in Fig. 13. Net delivery to the engine, however, was reduced appreciably, although the flow decreased less rapidly as the altitude increased.

With both an injector and a pressurising valve in the circuit, the net pump delivery exceeded that in the normal circuit at altitudes over 38,000 ft., further increase of altitude being accompanied by an increase of delivery instead of the usual decrease, but the injector itself did nothing to improve the system except at the highest altitudes.

It seems likely that an injector of more suitable design in the well of the tank would give better results, but the improvement will only be at high altitudes and at the expense of a reduction of net oil supply at lower altitudes.

By-passing the "hot-pot."

However necessary the "hot pot" may be for satisfactory cold starting and rapid warming up, it is certainly undesirable at working temperatures. It reduces the time available for air separation in the tank, and thereby almost certainly increases the aeration of the suction line.

Tests were made with the scavenge oil delivered to the main section of the tank by interchanging the tank connections to the air vent and the scavenge delivery inlet.

The oil seen in the sight glass in the pressure pump suction line appeared to be completely air-free, while the main oil pressure was increased by 7 lb. per sq. in. Flow measurements, Fig. 14, showed a pump delivery 15 per cent. higher than normal, and independent of altitude, and the maximum oil flow through the vent was reduced.

In the high pressure line there was no free air and only a small quantity of dissolved air. Satisfactory operation of the scavenging system at high altitudes, in spite of the increased quantity of oil with which it had to deal, was no doubt due to the absence of small bubbles. The total aeration in the scavenge line was reduced slightly, although the proportion of dissolved air was increased.

To obtain these advantages while still making use of the hot pot for cold starting and warming up, a thermostatic control valve

is necessary. Further tests were made with the viscosity valve connected so that the oil, when cold, by-passed the cooler and was delivered to the hot pot, while at working temperature the normal action of the valve transferred the oil flow through the cooler to the main tank. This arrangement gave increased pump delivery, as in the previous test, but the vent flow was increased, probably as a result of venting from the tank compartment to which the scavenge oil was delivered.

USE OF AN ANTI-FROTHING AGENT.

The addition of an anti-frothing agent to the lubricating oil has often been advocated. A number of tests were made with a proprietary agent of the silicone type, in the recommended concentration of one part in 100,000.

Observation showed almost complete froth suppression in both tank and sump under steady conditions. Oil flow along the vent was observed only under climbing conditions and even then was small. Little change could be observed in the high pressure or scavenge lines, but in the suction line bubble size appeared to increase with altitude, a fact not observed with undoped oil. At the higher altitudes, also, vibration could be felt in the high pressure line, accompanied by pressure fluctuations.

Figure 15 shows close agreement between scavenge and pressure pump deliveries under steady conditions, as would be expected with no vent flow. Because of this lack of vent flow, the pressure pump delivery above 10,000 ft. was reduced.

The suppression of froth in the sump increased the attainable altitude before scavenge pump failure. When failure finally occurred at 53,000 ft., the rise of sump oil level was accompanied by a sudden increase of pressure pump delivery, caused, no doubt, by the reduced aeration throughout the circuit when the scavenge pump inlets were completely submerged. This was not observed with undoped oil because excessive frothing always caused tests to be discontinued before a sufficient rise of oil level in the sump could occur.

The amount of dissolved air in the high pressure line was unchanged, but the free air was negligible. In the scavenge line, both free and dissolved air were reduced at intermediate altitudes, in agreement with the reduction of vent flow.

At high pump speed under climbing conditions, pressure pump delivery up to 41,000 ft. was reduced, on account of the reduction of vent flow. Scavenge failure occurred at about 42,000 ft., and a sudden increase of pressure pump delivery was again encountered.

The stability of the dope was tested by running continuously at 120°C., the altitude being maintained at 18,000 ft. A very slight increase of froth was detected after four hours, but no further increase was observed after ten hours.

It is concluded that, although the dope effectively suppresses frothing, it has no beneficial effect on pressure pump delivery.

CONCLUSIONS.

The effects of oil aeration on pump performance and on frothing depend on the amounts of free air and dissolved air in the oil and on the conditions tending to cause air to go into, or come out of, solution at different parts of the circuit. Measurements of aeration require separate determinations of free air and dissolved air and, since the air and oil tend to flow at different speeds, some form of sampling by displacement, such as in the meter described, is necessary if large errors are to be avoided.

Test results show that the oil may be supersaturated with air in some parts of the circuit; and that in other parts the dissolved air is less than that required for saturation, although free air may be present. The rates at which pressure changes occur, the amount of churning to which the oil is subjected, and the time available for air release or absorption, are important factors in determining the extent to which the air dissolved in the oil is greater or less than that required for saturation.

In the system tested, dissolved air in the scavenge line was carried through the tank to the pressure pump suction line, but free air was mainly released in the tank. With conditions corresponding to altitudes above 10,000 ft., the oil in the suction line was supersaturated, the amount of supersaturation increasing with altitude. The release of air from the oil forms froth in the tank and in the sump. When the tank fills with froth the excess is discharged through the vent pipe to the sump. The froth in the sump is extracted by the scavenge pumps except when, at high altitude conditions, the pressure

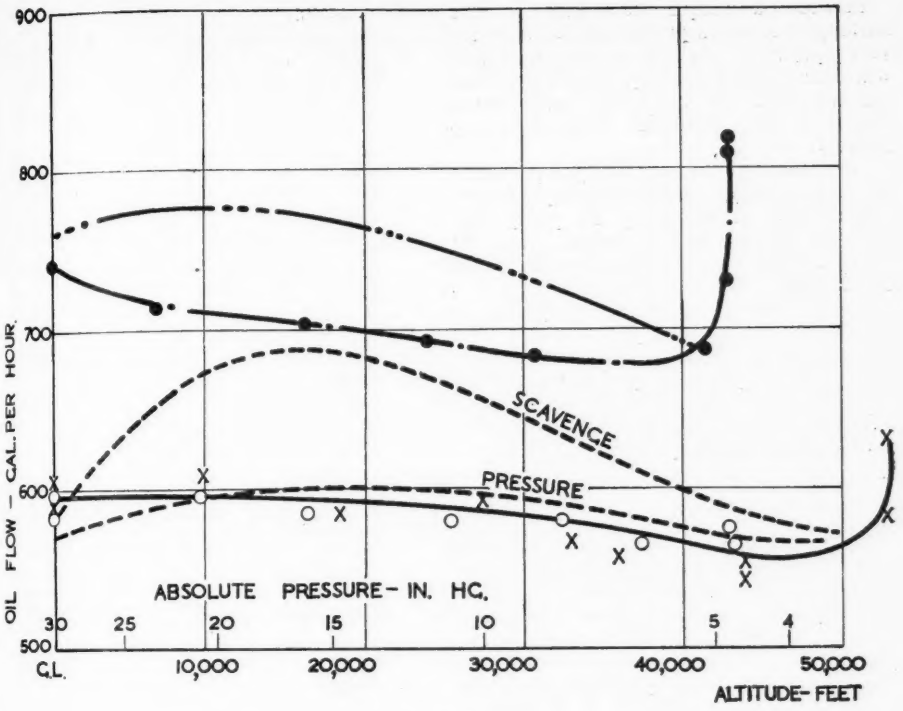

Fig. 15.

Effect of anti-frothing additive on oil flow.

"Normal conditions" { ---------- Undoped oil. ——— Doped oil.

O Pressure pump. X Scavenge pump.

Pump speed 2,500 r.p.m.; rate of climb 4,400 ft. per min. Pressure pump delivery. { ——— · · · ——— Undoped oil. ——— — ——— Doped oil.

falls so low that they fail to keep the sump clear, and the froth level builds up.

The mixing effect of the oil cooler in the scavenge pump delivery line was found to have an important influence on the formation of froth in the tank.

The delivery from the pressure pump falls at high altitude conditions, because of the increased volume of air in the pump suction line at the low pressure. Except when an aditional restriction was inserted in the pressure pump suction line, the performance of the scavenge pumps, not that of the pressure pump, was the limiting factor in the system.

The use of an artificial restriction in the pump suction line to simulate altitude conditions is not satisfactory. The restricting valve leads to release of dissolved air and expansion of free air in that part of the system, and creates an artificially high ratio of free air to oil at the pump inlet.

Of a number of expedients tested to improve pressure pump delivery and to reduce frothing, by-passing the "hot pot" in the oil tank was the most effective in increasing pump delivery. The oil in the pump suction line was almost free of air, and the pump delivery was independent of altitude pressure over the range tested.

Between a simple de-aerator in the scavenge line and a pressurising valve in the vent pipe, there was little to choose. Either will decrease tank frothing in systems where this is troublesome, but in the system tested they had little beneficial effect on pump delivery.

An injector in the pressure pump suction line, operated by oil from the pump delivery, was effective in increasing the pump inlet pressure, but in the form tested it was not efficient enough to increase the net flow to the engine.

The addition of an anti-frothing dope to the oil was effective in suppressing froth, but did not affect the amount of dissolved air and did not improve the performance of the pressure pump. The use of such a dope would be of value only where loss of oil by frothing is the major problem.

ACKNOWLEDGMENTS.

The work was all done at the Research Department of the Institution of Automobile Engineers (now taken over by the Motor Industry Research Association); the authors wish to express their gratitude to the former Automobile Research Committee of the Institution for granting them permission to publish the results. It is a pleasure also to acknowledge the help given by W. Michalski, Dipl. Eng. (Warsaw), A.M.I.Mech.E., to whom the design and successful development of the displacement aeration meter are largely due, and R. Griffiths, B.Sc. (Eng.), A.M.I.Mech.E., who collaborated in the experimental work. Thanks are due to the following firms for their helpful advice and criticism and for the provision of equipment for the tests: Armstrong-Siddeley Motors Ltd.; The Bristol Aeroplane Co. Ltd.; de Havilland Aircraft Co. Ltd.; Fairey Aviation Co. Ltd.; D. Napier & Son Ltd.; Rolls-Royce Ltd.; and The Thornton Aero-Engine Research Laboratory.

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REVIEW

Rockets and Space Travel: the Future of Flight Beyond the Stratosphere, by Willy Ley. Chapman and Hall Ltd. 374 pp., 14 photographs, 49 diagrams, bib. Price 18s.

Eighty-three years ago, the Royal Aeronautical Society was born into a Victorian world whose middle-aged citizens personally remembered Napoleon and to whom the assassination of Lincoln was a very recent memory indeed. The railway, steamship and electric telegraph were still the scientific marvels of the age; automobiles, radio, and electric power belonged to the fantastic future, and the heavier-than-air flying machine seemed almost as improbable as television, radar or the atomic bomb would have done, if their eventual appearance had even been suggested. The American scientist Simon Newcomb wrote, some twenty years *after* the R.Ae.S. was founded: "The demonstration that no possible combination of known substances, known forms of machinery, and known forms of force, can be united in a practical machine by which men shall fly long distances through the air, seems to the writer as complete as it is possible for the demonstration of any physical fact to be."

So much for the very early days of aeronautics: to-day, a new science—astronautics—is developing in a similar atmosphere of attempting the apparently impossible. It is true that the events of the intervening years have made the world rather more receptive to radical new ideas, so that the present pioneers of astronautics are perhaps less often dismissed as mere cranks and visionaries than were the early R.Ae.S. members. Still, any remaining hardened sceptics should feel less sure of themselves after reading Willy Ley's book, which has just been published in Great Britain after running through four editions in the United States. Also, the secret believers, who still think it more dignified to emphasise the immense difficulties, may find it easier to concede in public the eventual possibility of interplanetary travel, if such works as this help the layman to accept the idea.

Ley writes most entertainingly of almost every aspect of the subject; here we learn of the fascinating and surprisingly long history of the rocket, from its origins in Asia, through the Congreve war rockets of the early 19th century, to Peenemünde and the V.2. The account of the growth of the latter establishment and the German school of rocketry, from the pre-war pioneers such as Oberth and the German Rocket Society (V.f.R.), of which Ley was Vice-President, is particularly interesting.

Solid future progress will undoubtedly come from within an environment of bench testing, high temperature metallurgy, enthalpy/entropy charts, dissociation constants and supersonic gas dynamics—with the emphasis on a search for more knowledge of heat transfer at high gas temperatures and velocities. The well-produced book at present under review does not fill the long-felt want for a good technical work on these subjects, but it can be highly commended as a popular treatment of rocketry in general.

The simplified explanations of technical detail are nearly always clear and accurate, and the meteorological rocket, rocket applications in aeronautics, the space station and the eventual spaceship, are all discussed, with particular reference in the latter two cases to the celestial mechanics of the complicated orbits involved. Those professionally concerned with rockets should read this book for background; others, for its absorbing general interest and account of a subject of which the ultimate effects are going to be profound.

CORRESPONDENCE

SOME ECONOMIC FACTORS IN CIVIL AVIATION

Mr. Masefield has shown in his British Commonwealth and Empire lecture (October 1948 JOURNAL) that the economic possibilities of the jet-propelled aircraft as a commercial transport depend largely on the requirements for "stand-off" before landing, or diversion to an alternative airport, since for both short and long-range aircraft the fuel required to fulfil contemporary requirements of up to two or three hours at low altitude would displace the greater part, if not all, of the payload. A comparison of the fuel allowances for the plain jet and the propeller-turbine versions suggests that it might be possible to retain the advantages of the jets for high-speed cruising, while keeping the stand-off fuel within reasonable bounds, by installing an auxiliary propeller-turbine to operate only for this latter part of the flight, its use being somewhat analogous to that of the small engine used for patrol and manœuvring in high-speed light Naval craft, *e.g.* motor gunboats.

To justify the added complication of the extra power plant, it is necessary to show not only that there is an appreciable net saving in weight of propeller-turbine and fuel over jet engine fuel, but that some additional advantages are also offered. The example given below and others investigated show that these savings and advantages are in fact realised; they may be summarised as follows:—

1. For a stand-off time of about one hour at 1,000-5,000 ft. the weight of propeller engine plus fuel is equal to the weight of fuel alone for the jet engines.
2. For a time allowance of three hours (representing in practice say, 1½ hours stand-off plus a diversion flight) the saving in weight is about 10 per cent. of the take-off weight, equivalent to about half the payload for a short-distance type, or 80 per cent. for a long-distance type.
3. If the size of the auxiliary engine is increased by about 30 per cent. to meet "tropical summer" conditions, the weights are equal at 1½ hours and the saving at three hours is about 8 per cent.
4. For a time of ½ hour as in the "loitering" case for Naval aircraft there would be a net *loss* of 3-5 per cent., so that here the scheme would not be justified on its primary score of weight.
5. On the auxiliary engine alone the power will be adequate to give a safe rate of climb.
6. With the auxiliary engine in operation the take-off thrust will be increased by 30 to 40 per cent., increased power is also available for climb.
7. Although normally idle during cruising flight the auxiliary engine is always available in the event of failure of one or more of the jet engines.

It is possible that it would be advantageous for low-speed operation to arrange for the maximum amount of power to be put into the propeller, leaving little or no jet thrust; this would also facilitate installation of the engine as a "pusher" mounted in the tail of the aircraft to avoid disturbing the wing laminar flow. A secondary advantage of this engine position would be the "fin effect" of the propeller stabilising, allowing a reduction in fixed tail area. In cruising flight the air intake would be closed and the propeller feathered, the net drag increase being only about two per cent.

On the basis of the quantitative gains shown, it is suggested that the principle of using an auxiliary propeller-turbine offers a practical solution to the problem of operating jet-propelled aircraft under present-day air traffic conditions; if it should be contended that it is wrong to complicate even when "adding more lightness," then the answer may be that the whole principle of long "stand-off" allowances is the primary and greater evil and all efforts should be directed towards drastic reductions.

Example

4 jet-engined aircraft, all-up weight 66,700 lb.

Total thrust $4 \times 5{,}000 = 20{,}000$ lb.

Thrust/weight ratio 0.3; wing loading 40 lb./sq. ft.

Landing weight 80 per cent. maximum = 53,500 lb. w = 32 lb./sq. ft.

Auxiliary propeller engine 2,000 cruising E.H.P.; installed weight 3,800 lb.

Fuel consumption of two jet engines at best duration speed, 135 knots at 5,000 ft., 4,720 lb./hour.

Fuel consumption of propeller engine at same speed 1,260 lb./hour.

Reserve duration, hours	½	1	1½	2	2½	3
Jet fuel, lb.	2,360	4,720	7,080	9,440	11,800	14,160
Propeller fuel	630	1,260	1,890	2,520	3,150	3,780
Engine + fuel	4,430	5,060	5,690	6,320	6,950	7,580
Saving, lb.	− 2,070	− 340	+ 1,390	+ 3,120	+ 4,850	+ 6,580
% all-up weight ...	− 3.1	− 0.5	+ 2.1	+ 4.7	+ 7.3	+ 9.8
Saving with 30% increased engine size %	− 4.9	− 2.4	+ 0.2	+ 2.7	+ 5.2	+ 7.7

Rate of climb on normal power 250 ft./min.
„ „ „ „ maximum „ 550 ft./min.

R. K. Page, *Associate Fellow*

MR. MASEFIELD'S REPLY

This is a most interesting approach. But because of its increased complication and because of possible hazards in standing off and diverting on one engine in bad weather, it would not be likely to commend itself to operators.

The case against the suggested auxiliary propeller-turbine might be expressed as follows:—

(1) Increased prime cost.

(2) Costly and time-consuming in maintenance.

(3) Keeping the increased drag down to the region of two per cent. would be difficult to achieve and would require an elaborate installation. Besides creating as little drag as possible in high speed flight, the auxiliary unit must be fully de-iced as it will frequently be required to operate in icing conditions.

(4) Should more than one auxiliary be necessary, the force of the above objections is greatly increased.

Probably the best course will be to concentrate on development of the propeller-turbine until such time as improvements in air traffic control reduce demands on reserve fuel and so bring the plain jet into its own.

The second part of the last paragraph in Mr. Page's letter sums up the situation: long "stand-off" reserves *are* the primary evil and great efforts must be made towards drastic reductions. These can only be made by improved Air Traffic Control—not an easy thing to achieve but one of the most urgent problems which faces economic air transport development to-day.

A flight round the world on scheduled airlines which I have been fortunate in being able to undertake since writing my Commonwealth Lecture, has convinced me that there are many places where plain jet transports can operate as soon as they are available and reliable—in Australia for example. The fact that jet transports are being built emphasises the need to concentrate research and development on approach and landing aids and methods.

Incidentally, experience of the operating techniques of ten different airlines encountered in flying round the world, confirms the almost universal use of a constant-power cruise technique for the following reasons:—

(*i*) The need for higher cruising speeds than are possible using full long-range cruise technique (reducing power with weight).

(*ii*) Simplicity and convenience for crews.

(*iii*) The advantages from a maintenance point of view.

(*iv*) Limitations of r.p.m. imposed by propeller or airframe vibration.

The constant cruising powers normally adopted averaged about 57 per cent. of METO power (or about 47 per cent. of take-off power), while achieved specific consumptions averaged about 0.48 lb. per b.h.p. hour.

P. G. Masefield, *Fellow*

an appreciation

THE COUNCIL OF THE ROYAL AERONAUTICAL SOCIETY WISH TO THANK THOSE COMPANIES WHO, BY THEIR GENEROUS CO-OPERATION, HAVE DONE SO MUCH TO HELP IN THE PRODUCTION OF THE JOURNAL

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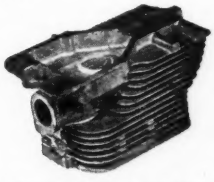

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The second part of the last paragraph in Mr. Page's letter sums up the situation: long " stand-off " reserves *are* the primary evil and great efforts must be made towards drastic reductions. These can only be made by improved Air Traffic Control—not an easy thing to achieve but one of the most urgent problems which faces economic air transport development to-day.

A flight round the world on scheduled airlines which I have been fortunate in being able to undertake since writing my Commonwealth Lecture, has convinced me that there are many places where plain jet transports can operate as soon as they are available and reliable—in Australia for example. The fact that jet transports are being built emphasises the need to concentrate research and development on approach and landing aids and methods.

Incidentally, experience of the operating techniques of ten different airlines encountered in flying round the world, confirms the almost universal use of a constant-power cruise technique for the following reasons:—

(*i*) The need for higher cruising speeds than are possible using full long-range cruise technique (reducing power with weight).

(*ii*) Simplicity and convenience for crews.

(*iii*) The advantages from a maintenance point of view.

(*iv*) Limitations of r.p.m. imposed by propeller or airframe vibration.

The constant cruising powers normally adopted averaged about 57 per cent. of METO power (or about 47 per cent. of take-off power), while achieved specific consumptions averaged about 0.48 lb. per b.h.p. hour.

P. G. Masefield, *Fellow*

an appreciation

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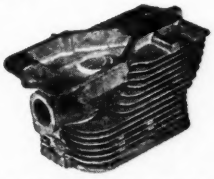

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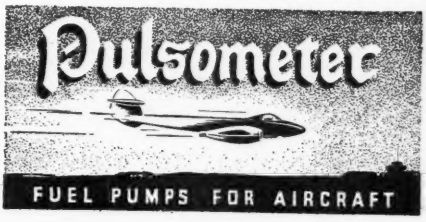

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The Journal is published monthly at the Offices of the Society, 4 Hamilton Place, Piccadilly, London, W1. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. Subscriptions per annum, £4 13 0 including postage; Single Numbers 7/6 or 7/9 post free. All communications for publication or Advertisements in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4 Hamilton Place, W1. The Society's Bankers are Messrs. Coutts & Co.

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NOTICES APRIL 1949

ANNUAL GENERAL MEETING

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday, 5th May 1949, at 5.30 p.m., in the offices of the Society, 4 Hamilton Place, London, W.1.

AGENDA

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets and Income and Expenditure Accounts of Aerial Science Limited and Aeronautical Trusts Limited for the year ended 31st December 1948.
3. To receive the names of those elected to Council for the years 1949-1952.
4. To announce the names of Fellows elected by the Council in accordance with Rule 4.
5. To elect the Auditors for the year 1949.
6. Any other business.

By Order of the Council,
J. LAURENCE PRITCHARD,
Secretary.

8*th April* 1949.

Note.—In accordance with Rule 17 any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served at 6 p.m.

SPECIAL GENERAL MEETING

Notice is hereby given that a Special General Meeting of voters of the Society will be held on Thursday, 5th May 1949, at 6.30 p.m., in the offices of the Society for the purpose of considering and, if thought fit, passing the following special resolution:—

"That this meeting adopts the revised By-laws proposed by the Council of the Society as the By-laws governing the Society."

By Order of the Council,
J. LAURENCE PRITCHARD,
Secretary.

8*th April* 1949.

Note.—In accordance with Rule 17 any member whose subscription has not been paid before the first day of April is not entitled to vote.

The proposed By-laws are being circulated to all voting members of the Society.

CONTENTS OF THE APRIL JOURNAL

Helicopter Discussion.

The Operational Point of View, by Wing Commander R. A. C. Brie, A.F.R.Ae.S., A.F.I.Ae.S.

Technical Problems of the Civil Helicopter, by Captain R. N. Liptrot, C.B.E., B.A.

The Fairey Gyrodyne, by J. A. J. Bennett, D.Sc., Ph.D., F.R.Ae.S.

The Bristol 171, by R. Hafner.

The Cierva Air Horse, by J. S. Shapiro, Dipl. Ing., A.F.R.Ae.S.

Effect of Aeration of the Oil on the Behaviour of an Engine Lubricating System under High Altitude Conditions, by E. Giffen, D.Sc., M.I.Mech.E., and H. R. Mills, Ph.D., M.I.Mech.E.

The Council have set aside an annual sum of £250 *for the award of premiums for papers published in the Journal and hope that members (or non-members) will contribute papers on their own special subjects.*

THE CHARTER GARDEN PARTY

The Society's Annual Garden Party, the Charter Garden Party, will be held on Sunday, 8th May 1949, at White Waltham Aerodrome, near Maidenhead, from 2.30 to 7 p.m.

The Garden Party this year is the first Garden Party following the grant of a Charter of Incorporation to the Society by H.M. The King.

This year special attention is being paid to the old flying days, so that members who have never seen some of the earlier machines flying will have an opportunity to do so. The leisurely flying of the 1920's and 1930's (and before then), and crazy flying and gliding and the like will revive memories for many and give a new slant on flying to others. And, just to give a modern touch, there will be the latest helicopter.

Application forms for tickets have been sent individually to members. A special train will leave Paddington and tickets at reduced rates will be available at the station.

EASTER HOLIDAYS

The offices of the Society will be closed from 5 p.m. on Thursday, 14th April 1949 until 9 a.m. on Tuesday, 19th April 1949.

SPECIAL NOTICE—WILBUR WRIGHT LECTURE

The Thirty-Seventh Wilbur Wright Memorial Lecture, to be given by Dr. Hugh Dryden, F.R.Ae.S., Director of Aeronautical Research to the National Advisory Committee of Aeronautics, on "The Aeronautical Research Scene—Goals, Methods and Accomplishments," on Thursday, 28th April 1949, will be held at the *Royal Institution, 21 Albemarle Street, London, W.*1, at 6 p.m. Tea will be served at 5.30.

Advance proofs of the paper, price sixpence, will be available.

FORMATION OF DIVISIONS OF THE ROYAL AERONAUTICAL SOCIETY

The Council of the Society in 1948 passed a Resolution to establish Divisions of the Society in the British Commonwealth and Empire.

Under this Resolution the Divisions have power to form Branches of the Royal Aeronautical Society, similar to those formed by the Society in Great Britain.

Members of the Division will all be full registered members of the Society and the Division has the power to act in most respects exactly as the parent body in London. The only important exception is the actual election of members so that a consistent standard will be set throughout the world. All such technical members will be elected by the Royal Aeronautical Society in London, but the Division will follow its own activities in the ways which best suit the country and local conditions.

The Council are glad to announce that Divisions have now been formed in Australia, New Zealand and South Africa.

LECTURE AT PORTSMOUTH

For the second time a major lecture of the Society is to be held at a Branch Centre. The first lecture under this new arrangement was given to the Birmingham Branch in October 1948. The second will be given before the Portsmouth Branch on Thursday, 21st April 1949 when Mr. R. R. Duddy will lecture on " High Lift Devices and their Use " at the Portsmouth Municipal College at 7 p.m.

The President-Elect of the Society, Sir John Buchanan, C.B.E., F.R.Ae.S., A.M.I.Mech.E., F.I.Ae.S., will preside at the meeting with Mr. E. C. Green, Chairman of the Portsmouth Branch.

It is hoped that as many members as possible of the Society and of the Branches in the Portsmouth District will attend.

LIBRARIAN

Applications are invited for the appointment of Librarian to the Society. Preference will be given to candidates who have L.A. qualifications and some experience of technical library work.

Salary will depend on qualifications and experience.

CORRECTION

The item in the Monthly Notices for February 1949 giving Elections to the Institute of the Aeronautical Sciences should have read as follows:—

Honorary Fellow—Captain J. Laurence Pritchard, Hon.F.R.Ae.S.

Fellow—Professor S. Goldstein, F.R.Ae.S.

THE AERONAUTICAL QUARTERLY

The Council have great pleasure in announcing that they have decided to publish an *Aeronautical Quarterly* beginning in May 1949.

The *Aeronautical Quarterly* will enable papers describing new and original work, or papers reviewing the progress in some specialised field of activity, to be published. Through the medium of its pages results of these researches will be made available to all workers or design groups concerned with aviation.

To ensure that the high standard set in the new *Quarterly* shall be reached and maintained, the Council have been fortunate in the assistance which has been given to them by an Editorial Board and many of the leading authorities in various branches of aeronautical engineering and science who have willingly offered their co-operation to act as referees on all papers submitted for publication.

The Council of the Society was greatly encouraged to sponsor this new venture by the response it received from members of the Society to its enquiry as to the need of such a publication. The future of the *Quarterly* is dependent on the support it receives; it is hoped, therefore, this support will be forthcoming from all sections of the Society, so that the success of the *Quarterly* is assured.

The price of each issue of the *Quarterly* will be 10/3 post paid to non-members and 7/9 to members. An application form for the *Quarterly* has been sent to members.

The contents of the first number will be:—

Flutter of Systems with Many Freedoms	W. J. Duncan
Control Reversal Effects on Swept-back Wings	H. Templeton
Estimation of the Effects of a Parameter Change on the Roots of Stability Equations	K. Mitchell
Note on Propeller-Turbine Reduction Methods	E. C. Pike
Determination of the Drag of Jet-Propelled Aircraft in Flight	G. W. Trevelyan and D. R. Blundell
Notes on the Linear Theory of Incompressible Flow Round Symmetrical Swept-back Wings at Zero Lift	F. Ursell
Calculation of Downwash Behind a Supersonic Wing ..	G. N. Ward

CONGRATULATIONS

The Council wish to congratulate the following Members on recent awards:

Sir Ben Lockspeiser, Fellow—Fellowship of the Royal Society.

Mr. Denis Howe, Graduate—Hele-Shaw Prize and Medal for 1948 awarded by the Institution of Mechanical Engineers.

MEMBERS' NEW APPOINTMENTS

Mr. J. C. Dykes, Associate Fellow—Assistant Technical Development Director (Engineering) British Overseas Airways Corporation.

Mr. Henry Davies, Fellow—Assistant Designer (Aircraft D.O.) Bristol Aeroplane Co. Ltd.

ASSOCIATE FELLOWSHIP EXAMINATIONS

The next Associate Fellowship Examinations will be held on 24th, 25th and 26th May 1949. All candidates who have registered with the Society will be informed individually of the detailed arrangements.

In reply to inquiries, Graduates elected before 1st January 1950 and those who have passed the Associate Fellowship Examination by that date will not have to take Part III of the new Associate Fellowship Examination.

FLYING DISPLAY AT BROUGH (EAST YORKS)

The Second Annual Flying Display organised by the Brough Branch will be held at Brough Aerodrome (kindly lent by Blackburn Aircraft Ltd.) on Saturday, 18th June 1949. Proceeds will be in aid of the R.A.F. Benevolent Fund and the committee are arranging a full programme of events which will again include the £100 Cirrus Trophy Competition for Cirrus-engined Auster aircraft. It is hoped that Branch officials and others will make a note of the date and if possible respond to the invitations which will be forwarded to them in due course.

The display will begin at 2 p.m. Gates open at 11 a.m.

Arrival time for visiting aircraft from 11 a.m.

Admission to public enclosure 2/6, cars and motor cycles 1/-.

Further information may be obtained from the Secretary:—

F. A. Wilkinson, A.F.R.Ae.S., Design Office,
Blackburn Aircraft Ltd.,
Brough, E. Yorks.

LECTURE PROGRAMME—SPRING 1949

Unless otherwise stated, lectures will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, London, S.W.1 (by permission of the Council of the Institution). Tea will be served at 5.30 p.m.

Thursday, 7th April 1949—Investigation of Aircraft Accidents in Relation to Aircraft Design, by Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S.

Thursday, 21st April 1949—High Lift Devices and Their Use, by R. R. Duddy, A.F.R.Ae.S. (*At the Portsmouth Municipal College at 7 p.m.*)

Thursday, 28th April 1949—THE THIRTY-SEVENTH WILBUR WRIGHT LECTURE:—

The Aeronautical Research Scene—Goals, Methods and Accomplishments, by Dr. Hugh Dryden, F.R.Ae.S., Director of Aeronautical Research to the National Advisory Committee of Aeronautics. (*At the Royal Institution, 21 Albemarle Street, W.1, at 6 p.m.*)

GRADUATES' AND STUDENTS' SECTION—LECTURE PROGRAMME 1949

Wednesday, 6th April 1949—The Trend of Jet Engine Development, by A. A. Lombard, A.F.R.Ae.S , Chief Designer (Projects), Rolls-Royce Ltd.

Tuesday, 19th April 1949—The Meaning and Measurement of Stability Derivatives, by P. T. Fink, B.E., Grad.R.Ae.S., Imperial College.

Tuesday, 3rd May 1949—Notes on Fighter Development 1936-1948, by Jeffrey K. Quill, O.B.E., A.F.C., Senior Test Pilot, Vickers-Supermarine Ltd.

Thursday, 12th May 1949—Pressure Cabins, by D. Cardwell, B.Sc., A.C.G.I., A.F.R.Ae.S., Royal Aircraft Establishment.

Meetings will be held in the Library of the Royal Aeronautical Society, 4 Hamilton Place, W.1, at 7.30 p.m. *The Library will not be open before 7 p.m.*

BRANCH NOTICES

BELFAST BRANCH

Tuesday, 12th April 1949—Annual General Meeting and Films.

Meetings are usually held in the Central Hall, College of Technology, Belfast, at 7 p.m.

BIRMINGHAM BRANCH

Friday, 29th April 1949—Annual General Meeting **at 7 p.m.** Followed by a Smoking Concert at 8 p.m. to which friends may be invited.

At the White Horse Hotel, Congreve Street, Birmingham.

BRISTOL BRANCH

Monday, 11th April 1949—The Aeroplane as a Commercial Product, by Captain K. J. G. Bartlett, Sales Director, The Bristol Aeroplane Co. Ltd.

Monday, 25th April 1949—Annual General Meeting and Film Show.

Meetings will be held in the Conference Room, Bristol Aeroplane Co. Ltd., Filton House, at 6 p.m.

BROUGH BRANCH

Wednesday, 13th April 1949—The Brabazon Aircraft, by F. H. Pollicut, Bristol Aeroplane Co. Ltd. *At Hull.*

In the Lecture Hall, Electricity Showrooms, Ferensway, at 7.30 p.m.

COVENTRY BRANCH

Wednesday, 27th April 1949—Annual General Meeting and Film—*in Trinity Hall,* at 7.30 p.m.

DERBY BRANCH

Monday, 2nd May 1949—Lubrication of Aero Gas Turbines, by J. G. Dawson, B.Sc., A.F.R.Ae.S.

At the Rolls-Royce Welfare Hall, Nightingale Road, Derby, at 6.15 p.m.

GLOUCESTER AND CHELTENHAM BRANCH

Thursday, 21st April 1949—Annual General Meeting. Followed by Film, Atomic Physics. *At Gloucester.*

In the Wheatstone Hall, City Library, Brunswick Road, at 7.30 p.m.

LEICESTER BRANCH

Wednesday, 13th April 1949—Annual General Meeting and Members' Papers.

In Room 104, College of Technology, The Newarkes, Leicester, at 7.15 p.m.

LUTON BRANCH

Wednesday, 6th April 1949—Film Show.

At the George Hotel, Luton, at 7.30 p.m.

MANCHESTER BRANCH

Thursday, 28th April 1949—Rocket Propulsion and Interplanetary Flight, by A. V. Cleaver, A.R.Ae.S.

In the Reynolds Hall at the College of Technology, Manchester, at 7.30 p.m.

PORTSMOUTH BRANCH

Thursday, 21st April 1949—High Lift Devices and their Uses, by R. R. Duddy. At the Portsmouth Municipal College at 7 p.m. *See also special notice on page 3.*

PRESTON BRANCH

Wednesday, 27th April 1949—Annual General Meeting.
In the Assembly Hall of the Technical College, Corporation Street, Prestwick, at 7.15 p.m.

READING AND DISTRICT BRANCH

Wednesday, 20th April 1949—Design for Production, by W. Thorne.
In the Abbey Gateway Rooms, Reading, at 7 p.m.

WEYBRIDGE BRANCH

Lectures

Wednesday, 6th April 1949—Historical Review of Aircraft Development, by Sir Frederick Handley Page, C.B.E., F.R.Ae.S.

Wednesday, 27th April 1949—Present-Day Problems in Safety Requirements, by W. Tye, O.B.E., B.Sc., F.R.Ae.S., Air Registration Board.

Wednesday, 18th May 1949—Junior Prize Lecture, by Branch members.

Wednesday, 1st June 1949—General Meeting.

Meetings will be held at Vickers-Armstrongs Ltd., Weybridge Works, at 6 p.m., unless previous notice is given.

Visits

The following visits are being arranged for which further particulars may be obtained from the Hon. Secretary, J. H. Sinclair, A.R.Ae.S., Vickers-Armstrongs Ltd., Weybridge, Surrey:—

21st and 28th May 1949—Tumblin Bay, Decompression Chamber, Wind Tunnels, Mechanical Test Department, Process Department, Erecting Shop, Drawing Office, Wisley Aerodrome.

11th June 1949—National Physical Laboratory, Teddington.

— **June 1949** (date to be arranged)—Tilbury Docks to view the new Orient liner *Orcades*.

— **July 1949** (date to be arranged)—Bristol Aeroplane Co. Ltd. to view the Brabazon.

ANNUAL SUBSCRIPTIONS OF MEMBERS

Members are reminded that their annual subscriptions became due on 1st January 1949. The rates are:—

	Home	Abroad
	£ s. d.	£ s. d.
Fellows	5 5 0	4 4 0
Associate Fellows	4 4 0	3 3 0
Associates	*3 3 0	*3 3 0
Graduates (aged 21-25)	2 2 0	2 2 0
Graduates (aged 26-28)	2 12 6	2 12 6
Students (aged under 21)	1 1 0	1 1 0
Students (aged 21 and over)	1 11 6	1 11 6
Companions	3 3 0	3 3 0
Founder Members	2 2 0	2 2 0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership.

Remittances should be made payable to either the Royal Aeronautical Society or Aerial Science Ltd.

INCOME TAX

In response to numerous inquiries from members with regard to a rebate on Income Tax for their subscriptions, the following is a copy of a letter received from the Principal Inspector of Taxes.

Ref. H.R.S. 34/C.I. 4420/63.

Dear Sir,

Further to your interview with Mr. Stonely at this office on the 19th July, I am now in a position to inform you that the Board of Inland Revenue will not raise objection to the allowance as an expense for Income Tax purposes of annual subscriptions paid by members who are:—

(i) Assessable under Schedule D of the Income Tax Acts in respect of professional or trading profits, subject to the decision of the Commissioners who make the assessment that such subscriptions are sufficiently closely related to the business on: or

(ii) Assessable under Schedule E in those cases only in which continual membership of the Society is an essential condition of the terms of appointment.

Yours faithfully,

(Signed) GEO. WILCOCK,
Principal Inspector of Taxes.

JOURNAL BINDING

The new prices of binding of Journals will be as follows:—

1948 Volume	14s. 6d.	(including packing and postage)
Previous Volumes ..	16s. 0d.	,, ,, ,, ,,
Cases for 1948 Volume	6s. 0d.	,, ,, ,, ,,

Journals should be sent direct to the Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Requests for cases, with remittances, should be sent to the Secretary at the Offices of the Society.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

NEW MEMBERS

The following new members have been elected:—

Associate Fellows

Eric Rae Alexander, Sidney Allen, Arthur William Babister, Edward Granville Broadbent, Jack Mulcock Buckeridge, Alfred Denis Snowden Carter (from Graduate), Francis Charles Case, William John Charnley, Ernest Joseph Redvers Clark, John Stanley Clarke, Francis Nugent Edney, Angus Eggleston, Kenneth

Essex-Crosby (from Student), Terence William Frederick Fairbairn (from Student), Gerald Gordon Fowler (from Graduate), Richard William Vessey Grandorge, Keith Percy Green, Austin Griffiths (from Associate), John Humphries (from Graduate), Walter Dickins Hunter (from Graduate), Lionel Cecil James (from Graduate), Hubert Anthony Krasinski, Cecil Beaumont Lewis, Eric Harold Mansfield, Maurice William Martin (from Graduate), James Denning Pearson, Pieter Abraham Peens, Ronald William Smith (from Graduate), Vivian Farrar Smith (from Associate), Ronald Alfred Smithers (from Graduate), Cyril Victor Stanmers, George James Thomson, Charles Keith Turner-Hughes (from Associate), James Carey Wallin (from Graduate), Kenneth Watson (from Associate).

Associates

Stanley George Driver, Thomas Wood Fazakerley, Arthur George Hancocke, Robert Gilbert Byford Hawkins, George Hatton King, Robert Nelson, Frank Parvin, Arthur Leighton Patterson, Harold Stanley Charles Rigby, Donald Albert Rix, Ernest John Roberts, Curt Bernd Alex Schiff (from Companion), George Edward Sibbit, Robert Smyth, Frederick Ernest Sparks, Herbert Charles Taylor, Howard Charles Tinney, John Whelan, Horace Mervyn Whitcombe.

Graduates

John David Arthur, Arthur Edward Mackenzie Barton, William Maurice Brady (from Student), Norman Oliver Brand (from Student), Edwin Arthur Broadhurst, Charles Basil Budd (from Student), Antony George Dixon, Alan Leslie Roy Fletcher, Christopher Huggins (from Student), Albert Ronald Mettam, William Norman Clyde Moore, Cecil James Olaf Moorhouse (from Student), Henry Harrison Morgan, Leslie Joseph Murrin, Dennis Rose, Michael William Salisbury (from Student), Peter John William Tuffs (from Student), Roy Ernest Withey, Ivor Edward Woodroffe (from Student).

Students

Kenneth Hedley Andrews, Richard Francis Beresford, John Chalmers, Peter John Farmer, Gerald Philip Gilbert, John William Howard Grant, Keith Gordon Hodson, Donald Geoffrey Johnson, William John Kenyon, William Stanley Mackie, Peter John Mettam, Thomas Nesbitt, Ronald David Page, Gordon Robert Parker, Anthony Brian Parry, Lionel Rossiter Pool, Hugh Gault Rice, John Scarlett, Louis John Stephenson, Arthur Brian Taylor, Robert John Trees, Arthur Francis Winstanley.

Companions

Edwin Gerard Davidson, Arthur James (from Graduate), Archibald William Alfred Prott Wilson, James Middleton Worthington.

ADDITIONS TO THE LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.a.355—Elementary Applied Aerodynamics. T. G. Whitlock. Oxford University Press. 1943.

B.e.47—Model Aeroplane Handbook. F. J. Camm. Newnes. 1949.

B.e.48—Control Line Flying. R. H. Warring. Marshall. 1949.

E.a.20—Engineering Tolerances. H. G. Conway. Pitmans. 1948.

E.b.133—Advances in Applied Mechanics. Vol. I. von Mises and von Kármán (Editors). Academic Press. New York. 1948.

E.b.134—Reissner Anniversary Volume; Contributions to Applied Mechanics. Staff of the Dept. of Aeronautical Engineering and Applied Mechanics, Polytechnic Institute of Brooklyn. J. Edwards, Ann Arbor, Michigan. 1949.

EE.h.41—Jet Propulsion and Gas Turbines. M. J. Zucrow. John Wiley & Sons. 1948.

G.f.32—Properties of Soft Solders and Soldered Joints. Research Monograph No. 5. J. McKeown. British Non-Ferrous Metals Research Association. 1948.
N.d.7—Military and Political Consequences of Atomic Energy. (3rd Impression, Revised.) P. M. S. Blackett. Turnstile Press. 1949.
*X.b.61—Whitaker's Almanack. Joseph Whitaker. 1949.

N.A.C.A. Technical Notes

1706—*Stability derivatives of thin rectangular wings at supersonic speeds. Wing diagonals ahead of tip mach lines. S. M. Harmon.*
1742—*Stability and control characteristics at low speeds of an airplane model having a* 38.7 *degree sweptback wing with aspect ratio* 4.51, *taper ratio* 0.54, *and conventional tail surfaces. V. E. Lockwood and J. M. Watson.*
1743—*Flight measurements of the stability, control, and stalling characteristics of an airplane having a* 35 *degree sweptback wing without slots and with* 80 *per cent. span slots and a comparison with wind-tunnel data. S. A. Sjoberg and J. P. Reeder.*
1744—*Two-dimensional compressible flow in conical mixed-flow compressors. J. D. Stanitz.*
1746—*Flow of a compressible fluid past a symmetrical airfoil in a wind-tunnel and in free air. H. W. Emmons.*
1753—*Evaluation of a fixed spoiler as a gust alleviator. H. C. Mickleboro.*
1754—*An analysis of the airspeeds and normal accelerations of Douglas DC-2 airplanes in commercial transport operation. W. G. Walker.*
1757—*Performance of conical jet nozzles in terms of flow and velocity coefficients. R. E. Grey and H. D. Wilsted.*
1759—*Effects of compressibility on normal-force, pressure, and load characteristics of a tapered wing of N.A.C.A.* 66*-series airfoil sections with split flaps. E. F. West, Jr., and J. M. Hallissey, Jr.*
1762—*Control considerations for optimum proportionment in turbine-propeller engines. M. F. Heidmann and D. Novik.*
1763—*Flight investigation of a combined geared unbalancing-tab and servotab control system as used with an all-movable horizontal tail. R. G. Mungall.*
1764—*Influence of tail length upon the spin recovery characteristics of a trainer-type-airplane model. W. J. Klinar and T. L. Snyder.*
1769—*The flexible rectangular wing in roll at supersonic flight speeds. W. A. Tucker and R. L. Nelson.*
1771—*The development of cambered airfoil sections having favourable lift characteristics at supercritical mach numbers. D. J. Graham.*
1772—*Theoretical basic span loading characteristics of wings with arbitrary sweep, aspect ratio, and taper ratio. V. I. Stevens.*
1773—*The effects of variations in Reynolds number between* 3.0×10^6 *and* 25.0×10^6 *upon the aerodynamic characteristics of a number of N.A.C.A.* 6*-series airfoil sections. K. Loftin, Jr., and W. J. Bursnall.*
1774—*Calculated performance of a compression-ignition engine-compressor-turbine combination based on experimental data. A. Mendelson.*
1775—*Hydrodynamic impact loads in smooth water for a prismatic float having an angle of dead rise of* 40 *degrees. P. M. Edge, Jr.*
1776—*Hydrodynamic impact loads in rough water for a prismatic float having an angle of dead rise of* 30 *degrees. R. W. Miller.*
1779—*Effects of antispin fillets and dorsal fins on the spin and recovery characteristics of airplanes as determined from free-spinning-tunnel tests. J. L. Gale and I. P. Jones, Jr.*
1780—*Charts for the conical part of the downwash field of swept wings at supersonic speeds. J. N. Nielson and E. W. Perkins.*
1783—*An analysis of the airspeeds and accelerations of Boeing B-*247 *and B-*247*D airplanes in commercial transport operation. W. G. Walker and I. K. Hadlock.*
1787—*Comparison of the structural efficiency of panels having straight-web and curved-web Y-section stiffeners. N. F. Dow and W. A. Hickman.*

N.A.C.A. Technical Reports

820—*Propellers in yaw. H. S. Ribner.*

823—*Experimental verification of a simplified vee-tail theory and analysis of available data on complete models with vee-tails. P. E. Purser and J. P. Campbell.*

828—*Bending and sheer stresses developed by the instantaneous arrest of the root of a moving cantilever beam. E. Z. Stowell and E. B. Schwartz.*

830—*A method for determining the rate of heat transfer from a wing or streamline body. C. W. Frick, Jr., and G. B. McCullough.*

831—*An analysis of the dissipation of heat in conditions of icing from a section of the wing of the C-46 airplane. J. K. Hardy.*

833—*General theory of airfoil sections having arbitrary shape or pressure distribution. J. H. Allen.*

836—*Bending-torsion flutter calculations modified by subsonic compressibility corrections. I. E. Garrick.*

838—*Consideration of dynamic loads on the vertical tail by the theory of flat yawing manœuvres. J. Boshar and P. Davis.*

842—*Some effects of compressibility on the flow through fans and turbines. W. Perl and H. T. Epstein.*

845—*Quantitative treatment of the creep of metals by dislocation and rate-process theories. A. S. Nowick and E. S. Machlin.*

A.R.C. Reports and Memoranda

2319—*High-speed lift measurements on a thick aerofoil fitted with a spoiler. P. J. Wingham.*

The following reports have also been received:—

National Research Council of Canada

AN-2—*Estimation of wing torsional divergence speed with downwash correction. A. H. Hall.*

AR-5—*Wind tunnel corrections in ground-effect tests. J. Sanders.*

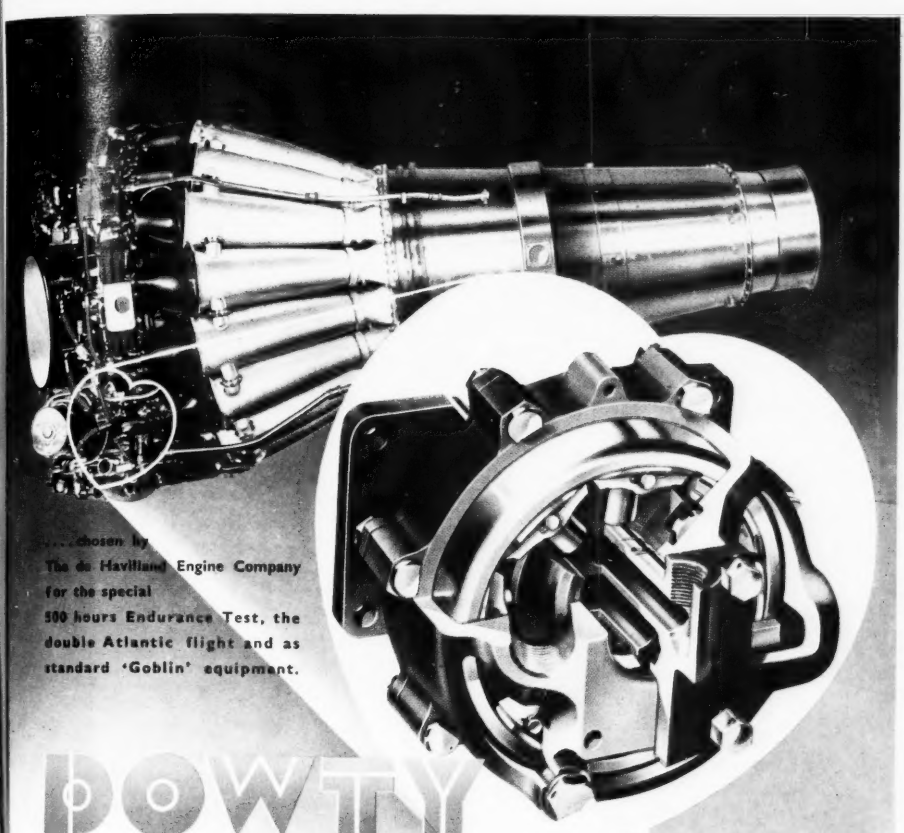
AR-6—*Wing flutter experiments with vibrations in stiffness and distortion form. A. H. Hall.*

Publications Scientifiques et Techniques du Ministere de l'Air

223—*Le calcul de la couche limite laminaire ou turbulente en fluide compressible. A. Oudart.*

J. LAURENCE PRITCHARD,
Secretary.

Made and Printed in Great Britain by the Lewes Press, Lewes, Sussex.



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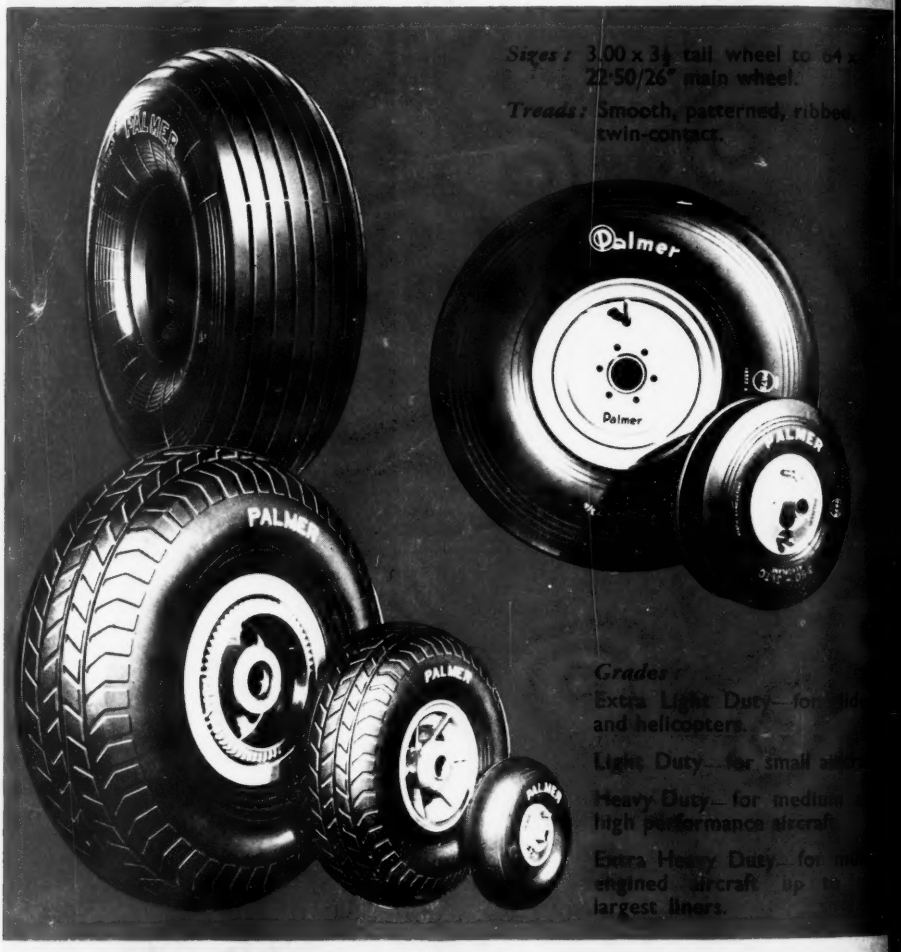

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Printed by the Lewes Press (Wightman & Co. Ltd.), Friars Walk, Lewes, England, and Published by The Royal Aeronautical Society, 4 Hamilton Place, London, W.1, England.